OLUME 102 PART A NUMBER 6 DECEMBER 1955

# The Proceedings

OF

# THE INSTITUTION OF ELECTRICAL ENGINEERS

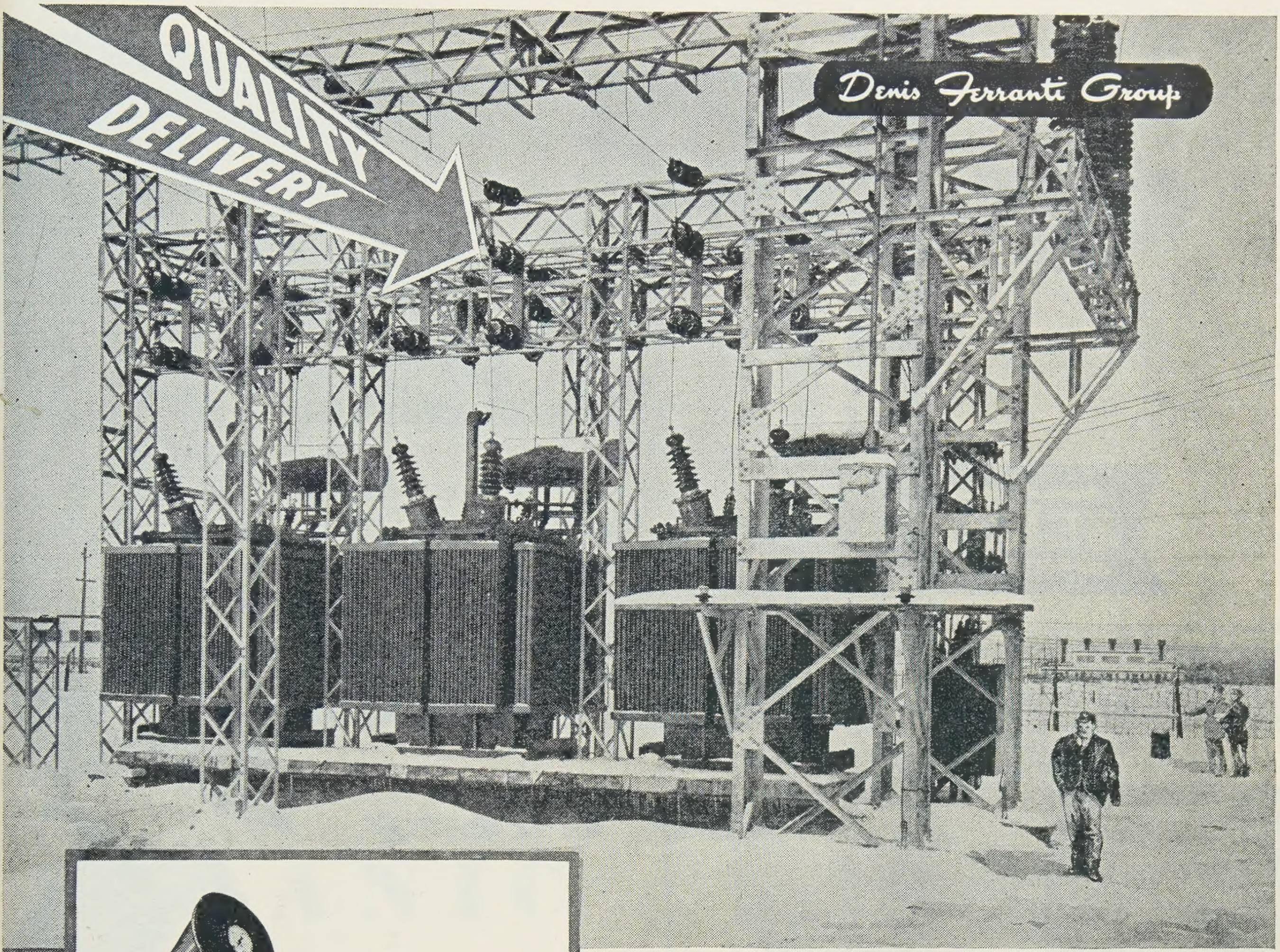
FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

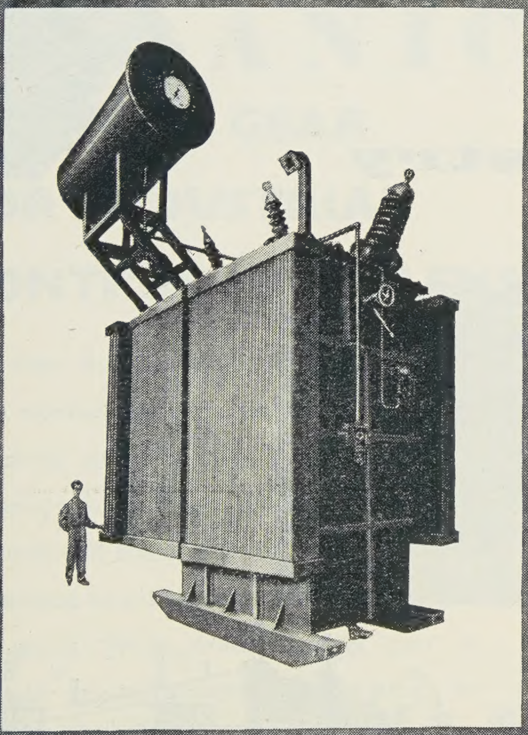
## PART A

POWER ENGINEERING

SAVOY PLACE · LONDON W.C.2

*Price Seven Shillings and Sixpence*


QUALITY
DELIVERY
Denis Ferranti Group

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for every
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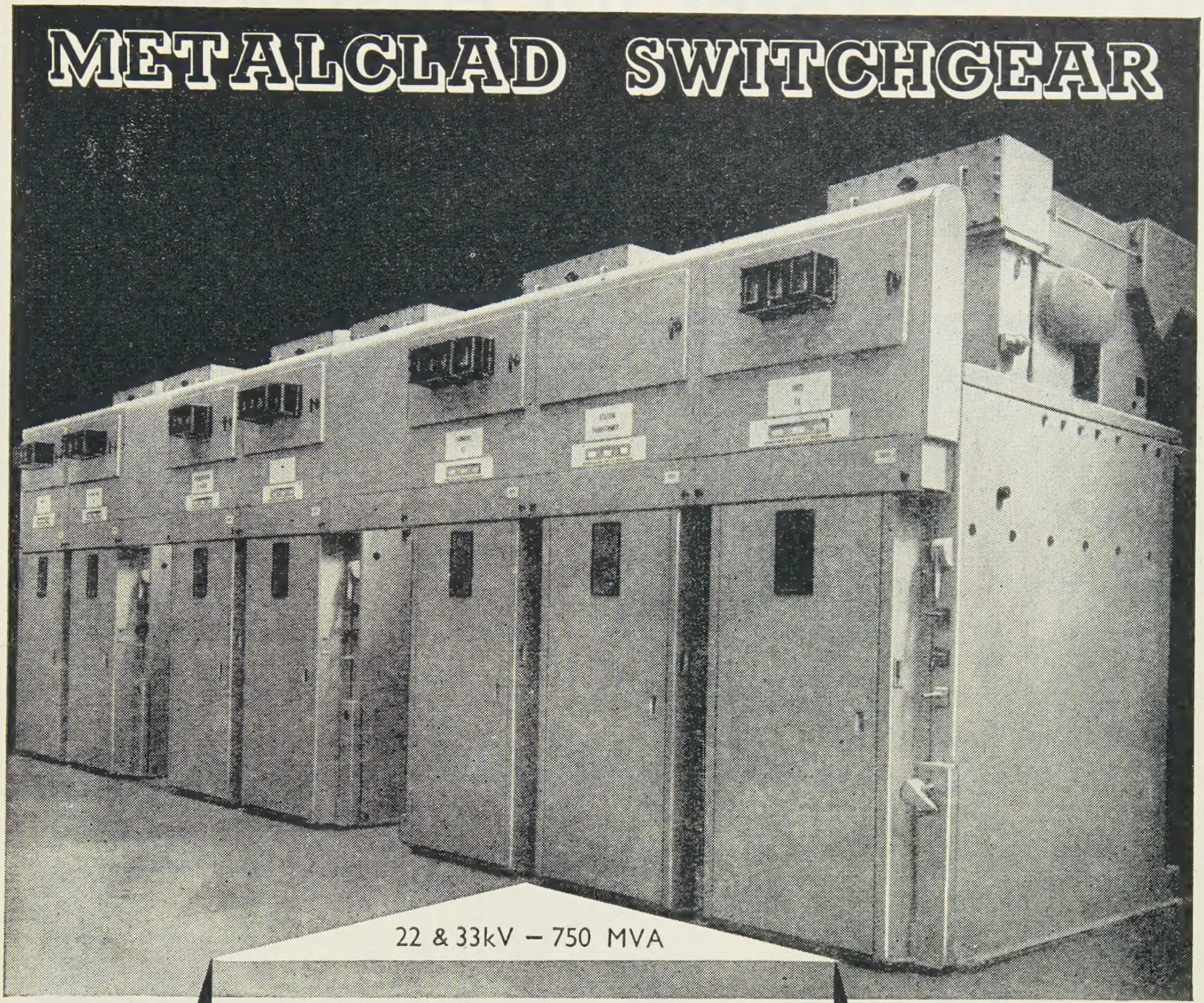



22 & 33kV – 750 MVA

Part of a type-L42T
22-kV single-busbar
metalclad switchboard
with vertically-isolated
magnet-operated 3-phase
oil-break circuit-breakers

SEND FOR PAMPHLET No. 1273

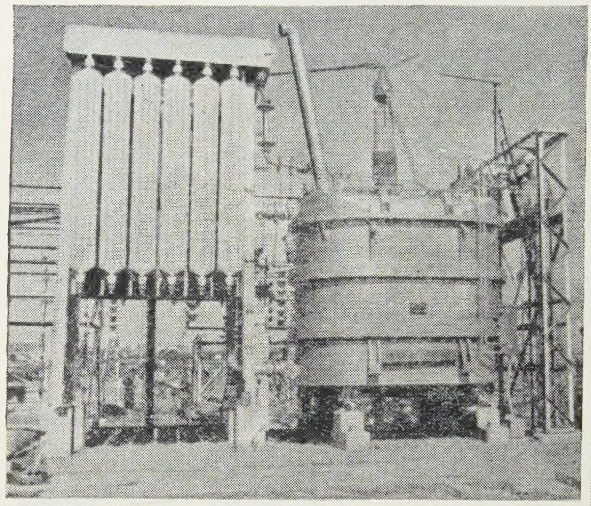
**Reyrolle**

A. REYROLLE & COMPANY LIMITED • HEBBURN • COUNTY DURHAM • ENGLAND

# More Power for Australia...

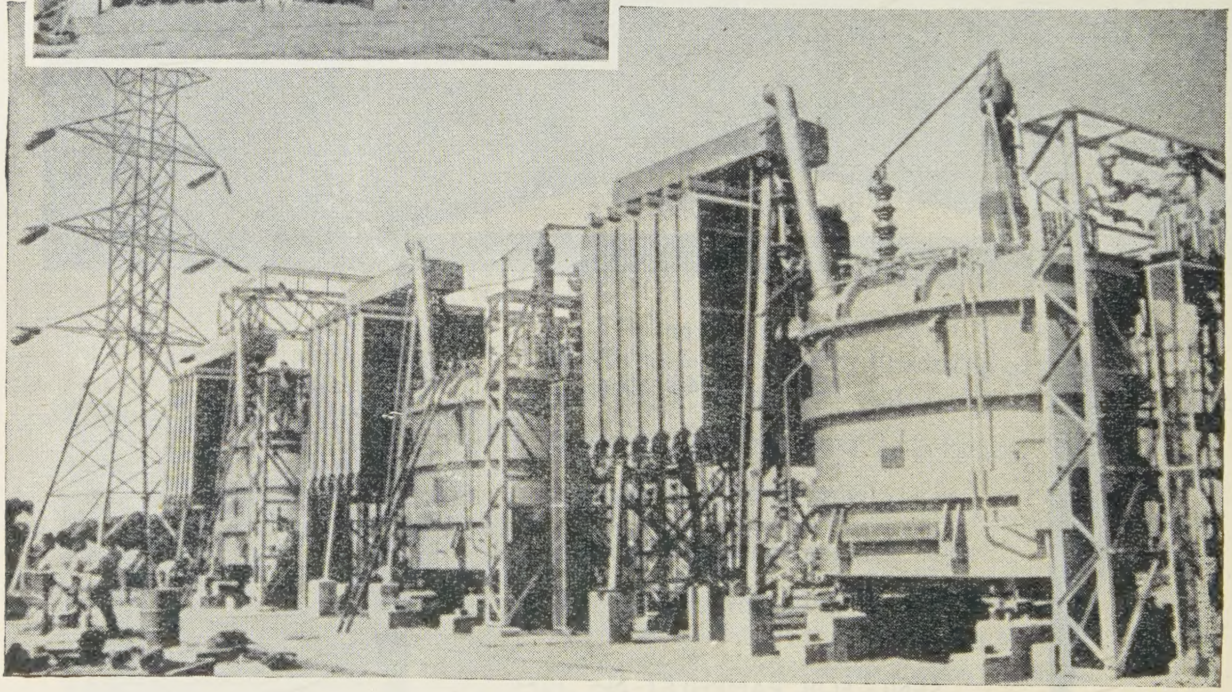
B T-H

## 220 kV TRANSFORMERS



Industrial expansion in Australia has, inevitably, increased the demand for electric power. As part of their development programme, the State Electricity Commission of Victoria are installing a total of seventeen BTH 220 kV, 15 MVA, single-phase transformers at substations in the Melbourne area.

*The illustration shows part of the installation at Brunswick substation with, inset, one of the BTH units.*



BTH manufacture all types of transformers—also cast-in-concrete and oil-immersed reactors, step-voltage regulators, arc-suppression coils, oil-testing sets, oil filter presses.

**BRITISH THOMSON-HOUSTON**

THE BRITISH THOMSON-HOUSTON COMPANY LIMITED · RUGBY · ENGLAND

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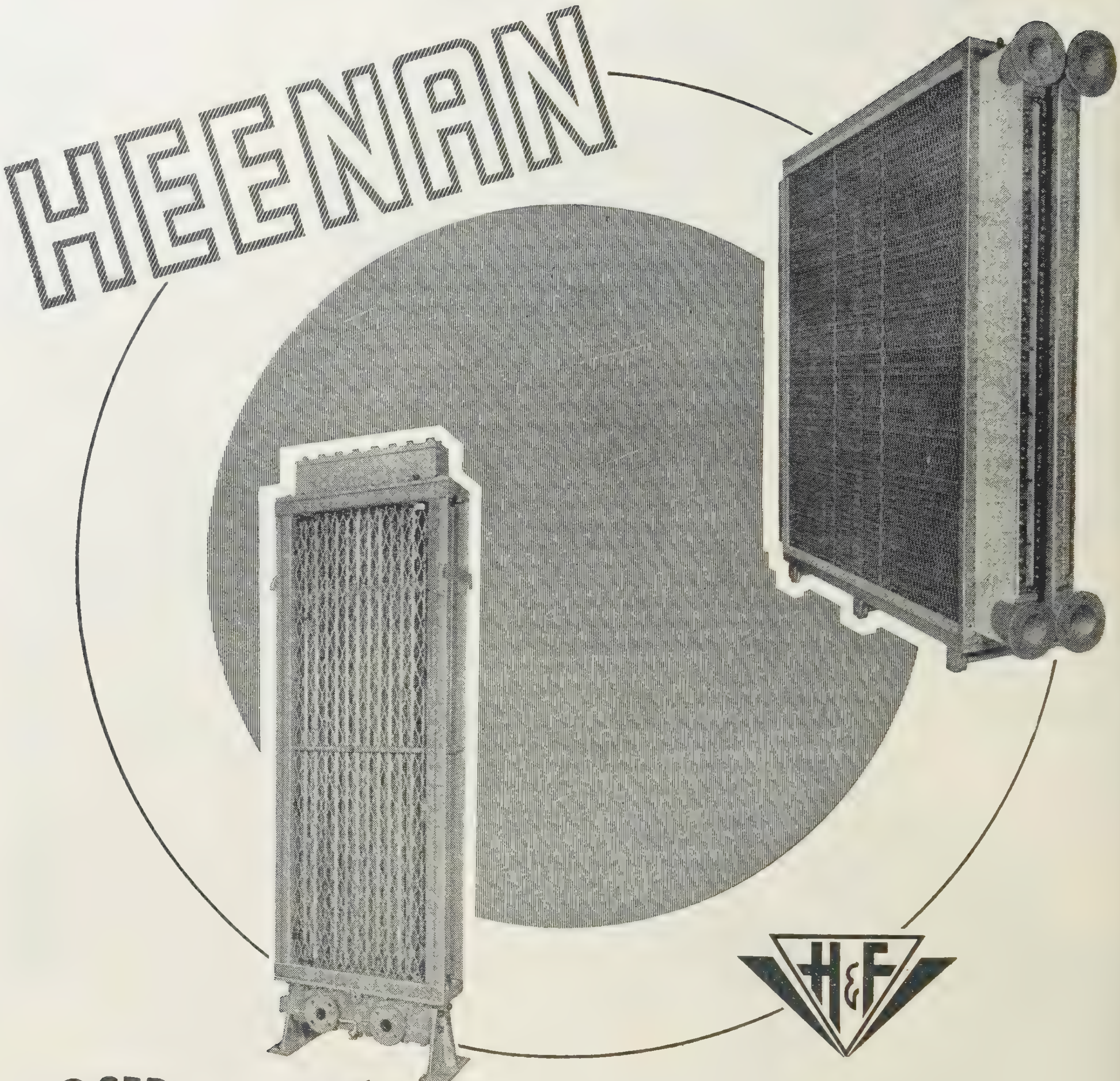


CLOSED CIRCUIT

# AIR COOLERS

**Lengthy experience in practical design**
**Wide variety of ducting and damper layouts**
**Highly efficient cooling surfaces**
**Heavy and robust construction**
**Special attention to ease of access and maintenance**

*(The names 'Heenan' and 'Froude' are registered trade marks of the Company)*

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NOW—

Green Seal

## *Safety* TRANSFORMERS

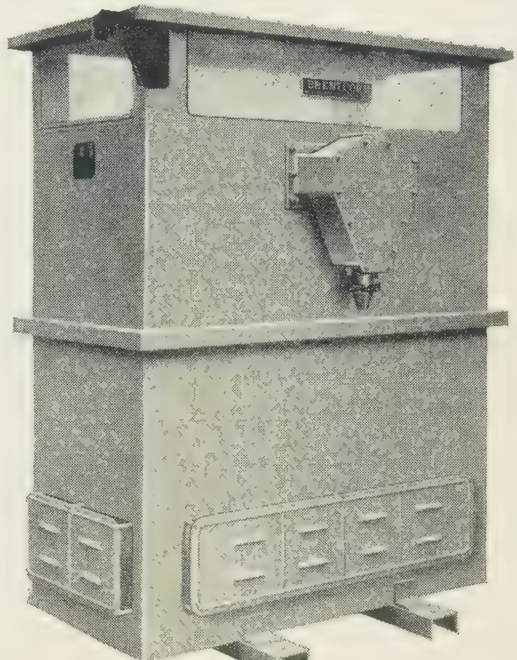
*using 'Class H' insulation*

## 'or greater safety ınd reliability . . .

**;RENTFORD TRANSFORMERS LTD., ınnounce a new range of dry (oil-less) ransformers using glass, ceramics ınd other similar inorganic materials mpregnated with silicone resins.**

*This latest development in transformers offers greatest ever safety for:—*

*Atomic Energy Establishments — Chemical Works — Oil Refineries — Explosives Factories — Blocks of Flats — Schools — Passenger Vessels — Tankers — Coal Mines — Radio, Radar and Television Stations — Underground Railways.*



*Two types are available in a range of sizes*

| | kVA. | Voltage |
|---|---|---|
| Class ANH (Ventilated) | Up to 3,000 | Up to 15 kV |
| Class GNH (Sealed in Nitrogen) | Up to 2,000 | Up to 15 kV |

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*offer all these advantages:—*

- *Safest transformers ever developed*
- *No fire or explosion hazard*
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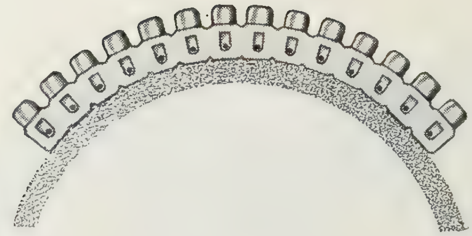
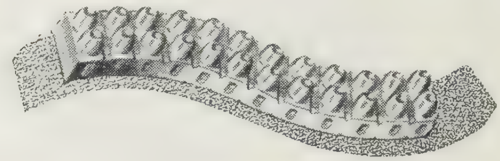
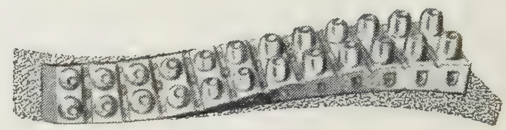




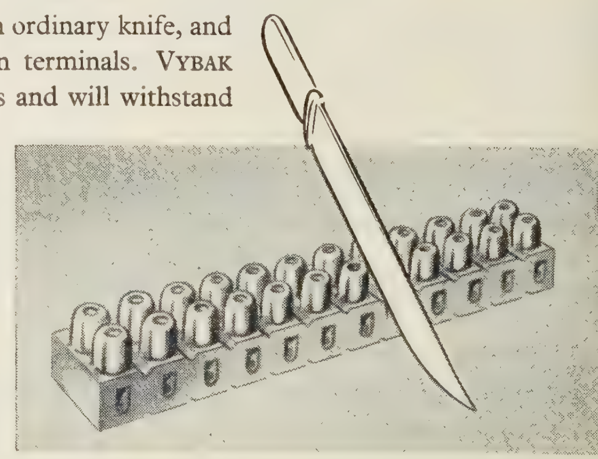













FERRANTI
FMP

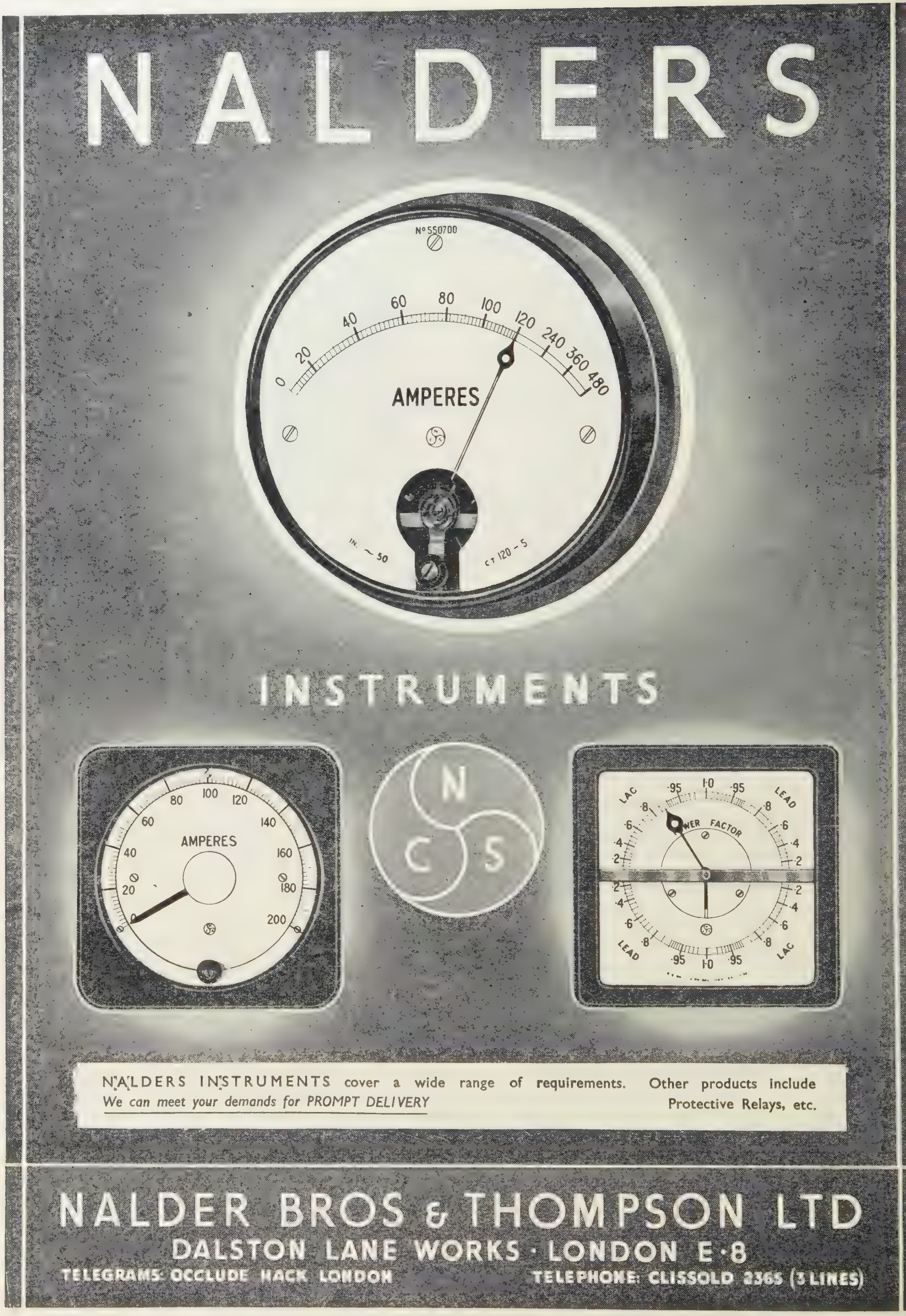
# PREPAYMENT METER

The Ferranti FMP Prepayment Meter has a strong appeal to the Supply Engineer. The meter is built to meet modern requirements. It is robust in construction, using essential material liberally and having operating characteristics of the highest order. Ferranti also manufacture the FMP2 meter with Fixed Charge Collector Mechanism.

FERRANTI

**FERRANTI LTD · HOLLINWOOD · LANCS**
London Office: KERN HOUSE, 36 KINGSWAY, W.C.2

FM 122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NALDERS INSTRUMENTS cover a wide range of requirements. Other products include
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Protective Relays, etc.
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DALSTON LANE WORKS · LONDON E·8
TELEGRAMS: OCCLUDE HACK LONDON
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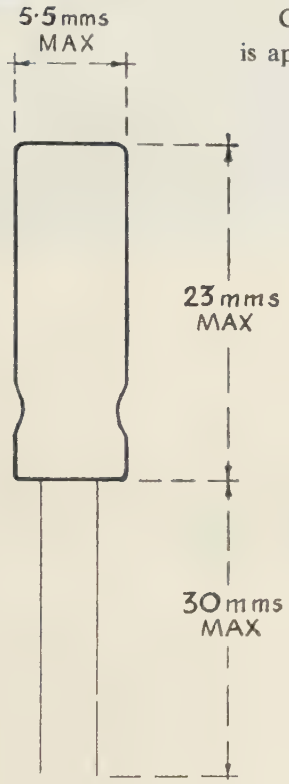
SIEMENS ELECTRIC LAMPS AND SUPPLIES

# COLD CATHODE DIODES

First of a new range of miniature Cold Cathode Diodes, the Siemens 2NIa is applicable to a variety of electronic functions including :—




Simple relaxation oscillators

Simple Pulse generating circuits

Gating circuits

DC. level changers (*for use in direct coupled amplifiers, etc.*)

Information storage

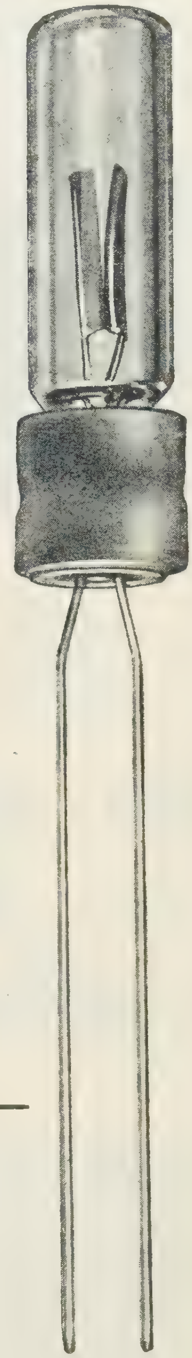
Test Probes

Radio Frequency Indicators

Coupling Devices

Low current stabilizers

Blown Fuse indicators



## *CHARACTERISTICS*

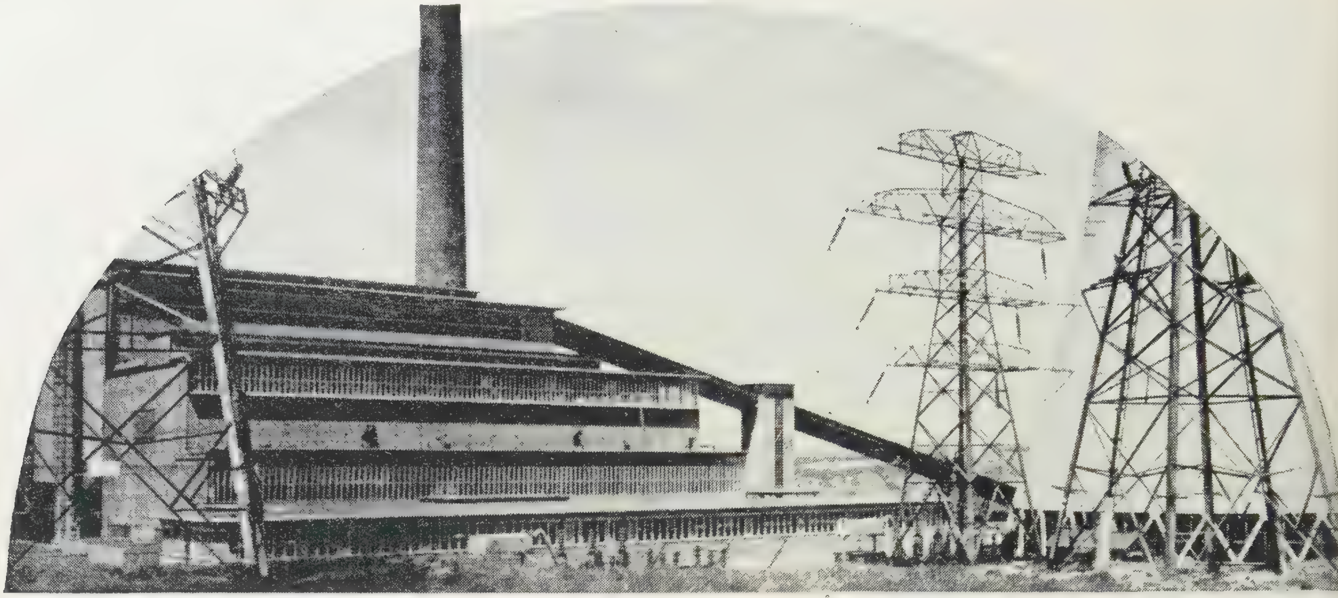
| | | | |
|---|---|---|---|
| Maximum Striking Voltage | = | 85 | V |
| Maximum Maintaining Voltage at 0.5mA | = | 65 | V |
| Maximum Continuous Current | = | 1 | mA |
| Nominal Ionisation Time | = | 50 | μs |
| Nominal Deionisation Time | = | 150 | μs |

***Details of application and further information from :—***

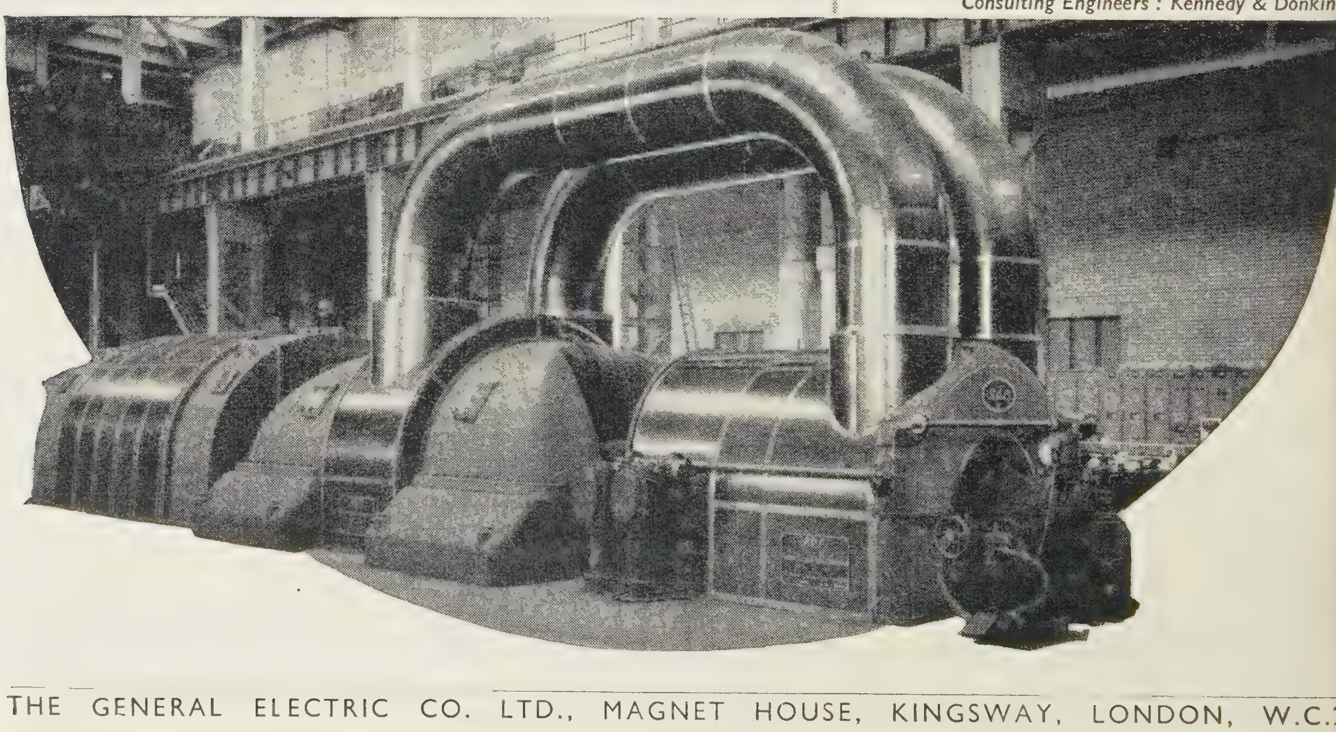
**SIEMENS ELECTRIC LAMPS & SUPPLIES LIMITED**

**38-39 UPPER THAMES STREET, LONDON, E.C.4.**

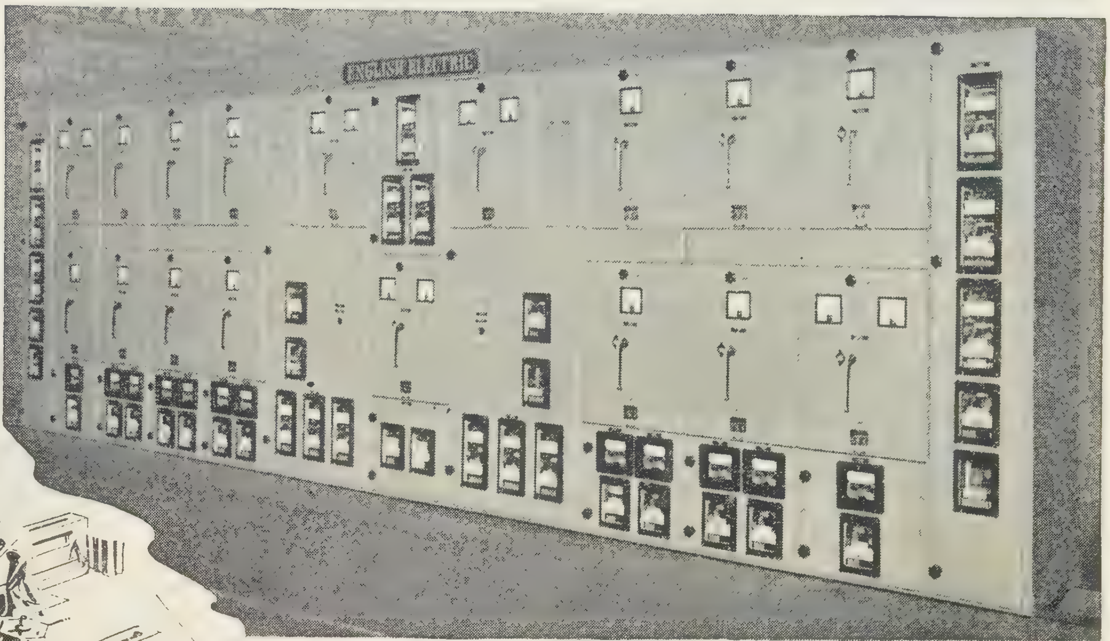
*Member of the A.E.I. Group of Companies.*

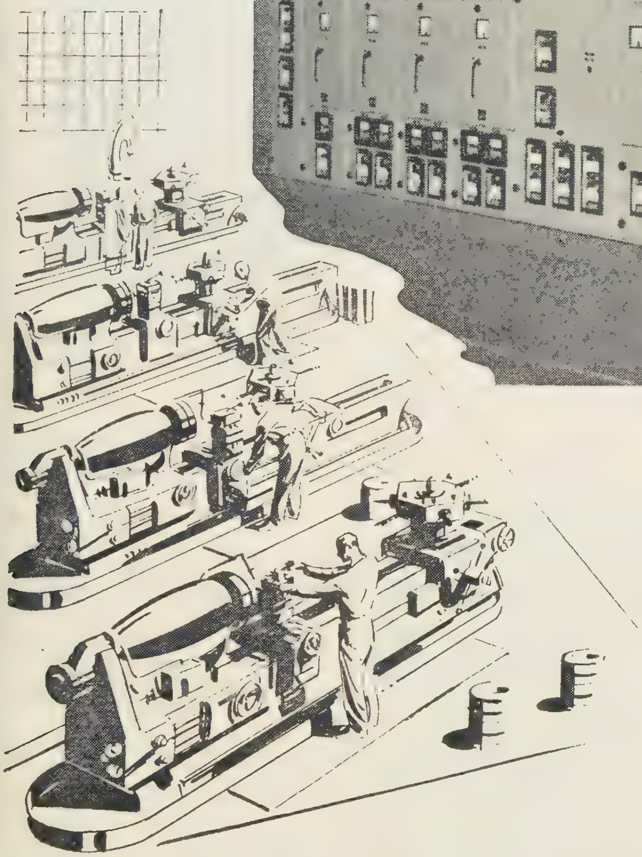






# Electrical distribution for the up-to-date factory



'ENGLISH ELECTRIC' medium voltage air circuit-breakers, eminently suitable for the control of factory electrical distribution systems are installed in industrial concerns throughout the world.

The switchboard illustrated comprises 'ENGLISH ELECTRIC' 600 amp 15 MVA type OB2 air circuit-breakers for service up to 660 volts.

# 'ENGLISH ELECTRIC'

## switchgear

THE ENGLISH ELECTRIC COMPANY LIMITED, QUEENS HOUSE, KINGSWAY, LONDON, W.C.2

*Switchgear Department, Liverpool*

WORKS: STAFFORD · PRESTON · RUGBY · BRADFORD · LIVERPOOL · ACCRINGTON

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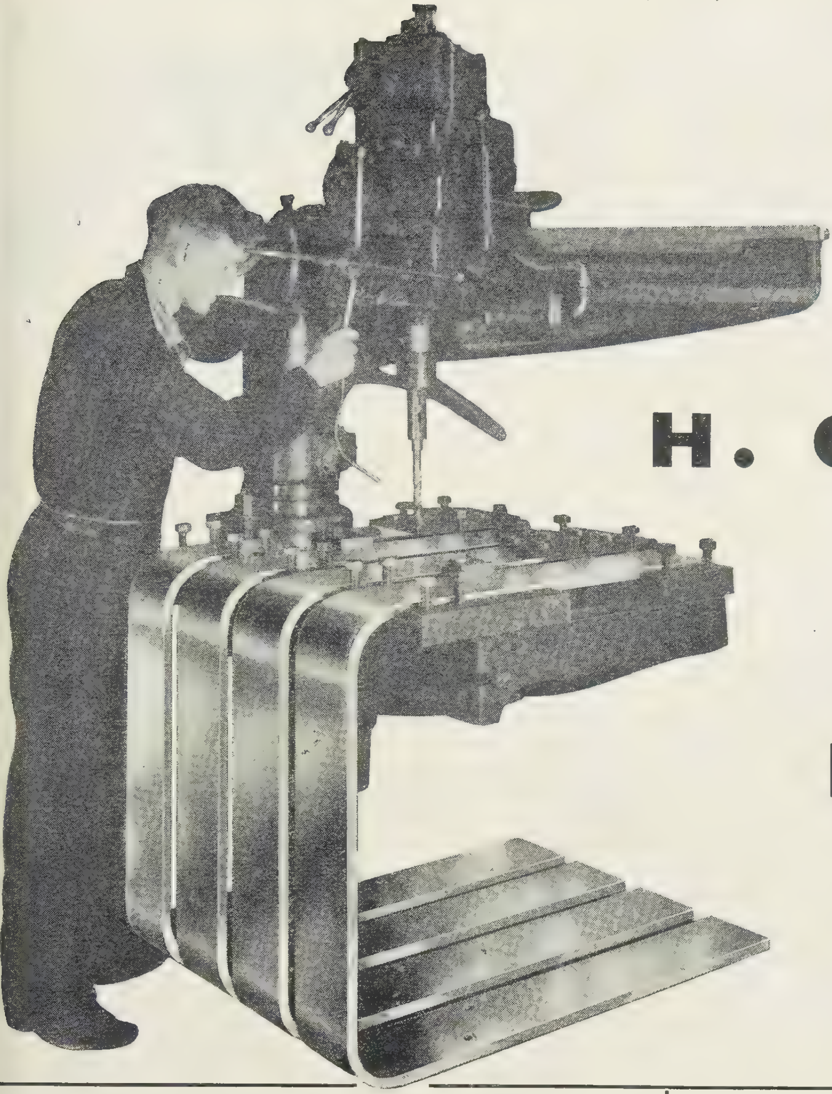

# Send TO-DAY!

## BROCHURE ON THE NEW VARLEY PEAK VOLT METER


The measurements and appreciation of transient voltages have been a problem to designers for years. That they exist has been common knowledge, but the extent of their peak has been difficult to ascertain owing to the lack of a suitable instrument.

Recent developments of Thyratron technique have made it possible to produce a compact and portable instrument so that the peak voltages can readily be determined either in the laboratory or in the field

The Varley Peak Volt Meter fills this need and is an essential piece of equipment for any electrical laboratory or test department. It is one of the very few instruments of its kind on the market, measuring transient voltages from 5 to 35,000 volts to an accuracy of approximately 10%.

**PRICE £35 NET**

## The Specialists in Electro-Magnets

*We also supply Transformers, Solenoids, Relays, Mercury Switches, Permanent Magnets and Heating Equipment.*

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TEL.: WOOLWICH 1422-6

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Please send me free of charge, details and specifications of the new Varley Peak Volt Meter.

NAME ____________________

COMPANY ____________________

ADDRESS ____________________ IEE

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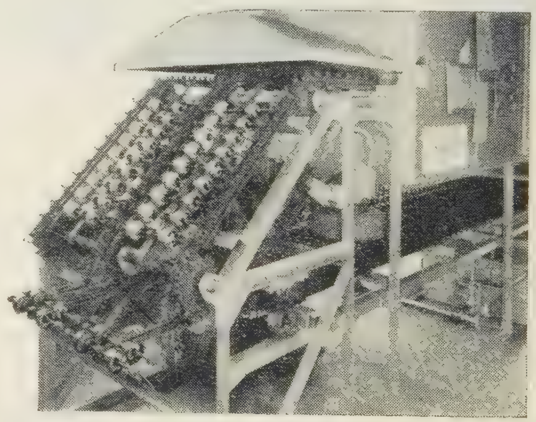
# 60 YEARS SERVICE

In 1894 the power of Niagara Falls was harnessed—and the first power utility was born. And in 1894, simultaneously with the advent of the electrical power industry, The Sterling Varnish Company—the world's first specialists in insulating varnishes—was founded. Since those early days we have always kept one move ahead of the needs of the electrical industry, and today we offer the complete insulating varnish service—with as many different grades as there are specialised requirements, and unrivalled laboratory and engineering facilities for the development of ever better methods of application. May we have your request for further details?



*In this Plant for Messrs. Hoover Ltd., 275 vacuum cleaner armatures per hour are impregnated with insulating varnish by the revolutionary patented Zanderoll Process.*

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*London Office and Warehouse:*
*6 LONDON RD., BRENTFORD, MIDDX.*
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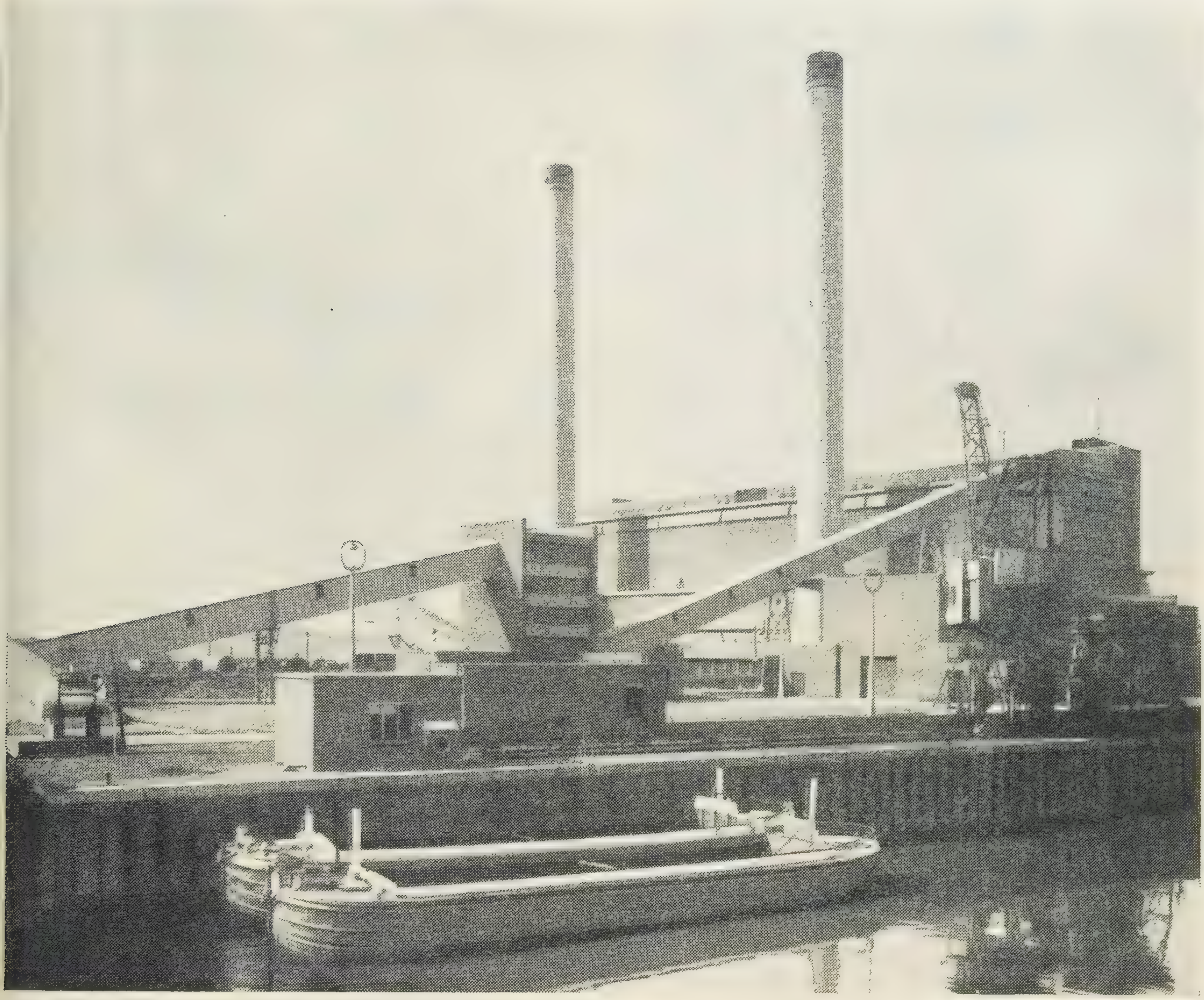
dm ST 3

# Railways are *more* than Trains



*Doncaster Power Station. Boilers, Coal Unloading & Handling Plant were supplied by Mitchell Engineering Ltd.*

**ELECTRIFICATION** of the railways is linked closely to the resources of our power stations. They in turn depend on the efficiency of steam generating plant, handling plant, etc. With 35 years' experience of power station engineering — and such other specialized work as tunnelling, docks, harbours and mechanical handling equipment of all kinds — **MITCHELL** are today entrusted with a major share of the contracts issued by the Central Electricity Authority. Mitchell's accumulation of '*know how*' is playing a growing part in the economical expansion of Britain's capital resources.

**MITCHELL**

*35 years of Progressive Development for Power Supply, Civil Engineering and Mechanical Handling Equipment*

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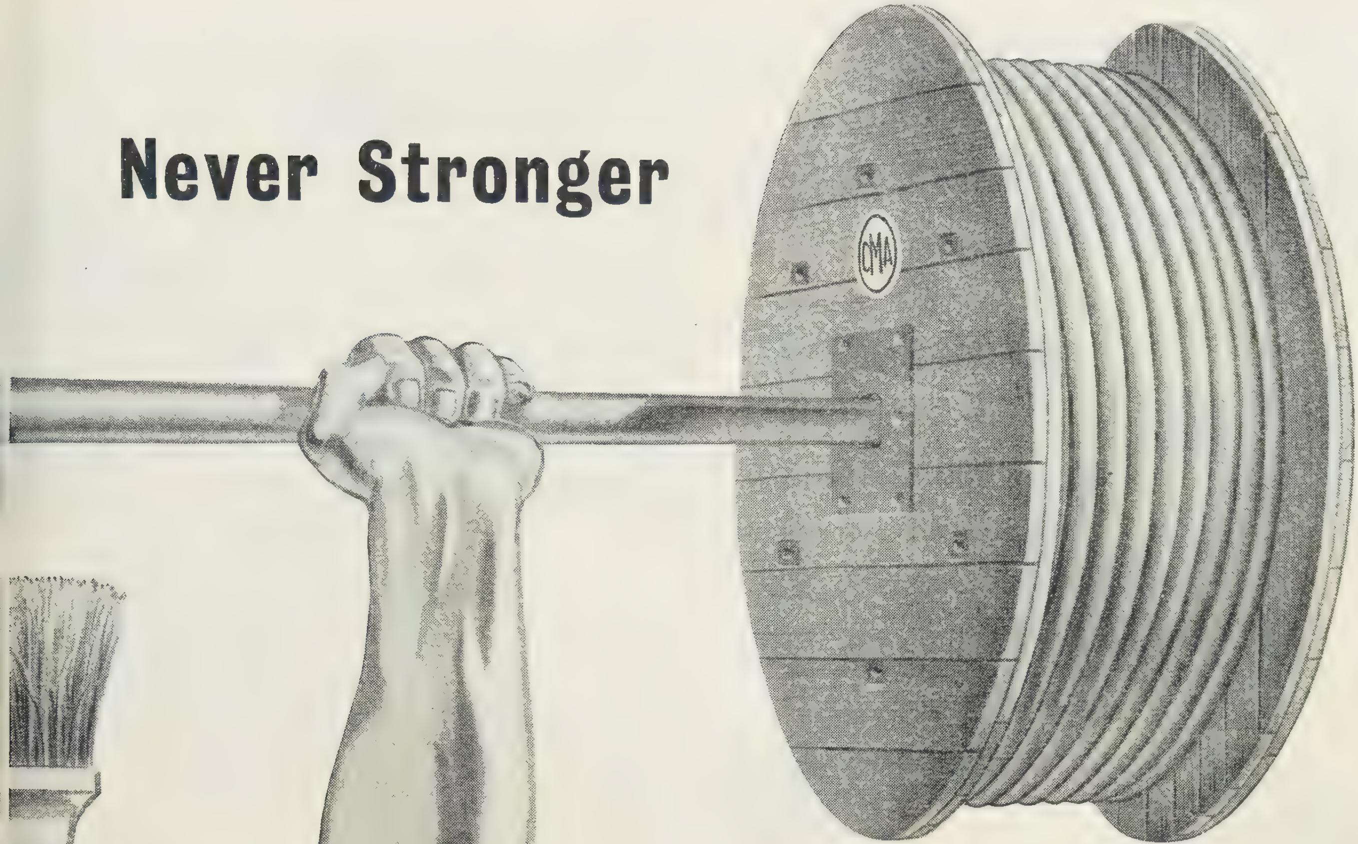
# Never Stronger




The Cable Makers Association has never been stronger. It has been concerned in all major advances in cable making during the 55 years it has been in existence. Much remains to be accomplished. The C.M.A. is ever conscious of its responsibility for supplying high quality cables to the world, in fostering fruitful channels of communications in research amongst its 17 members and also to the many government sponsored and other important technical committees on which C.M.A. members serve.

Technical advice concerning cables will be freely given and the C.M.A. will gladly put you in touch with suitable manufacturers.

## *Insist on a cable with the* C·M·A *label*

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# SIEMENS R.I.N.D. CABLE


## *A New Development*

The R.I.N.D. Cable is RADIALLY IMPREGNATED under strictly controlled conditions thereby presenting a new technique in cable manufacture. The paper insulation is thoroughly dried and impregnated, but contains no superfluous compound. Dimensions in accordance with B.S.480: 1954 specification for normal belted type cables.

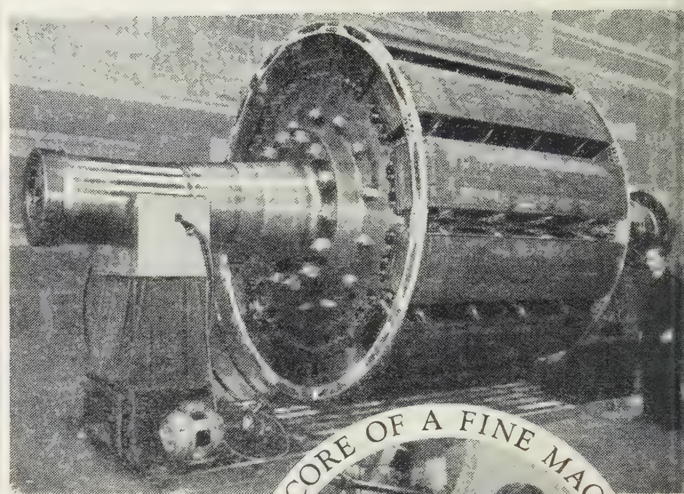
R.I.N.D. cable is suitable for general use, but is indispensable for situations where steep gradients and high ambient temperatures are encountered. No special jointing method is necessary, standard joint boxes are used.

SIEMENS BROTHERS

***SIEMENS R.I.N.D. CABLE . . .***

- *Passes Drainage Test in B.S.480/1954*
- *Has no critical temperature*
- *Gives no overload troubles*
- *Causes no difficulty with bending*
- *For voltages up to and including 11,000*

SIEMENS BROTHERS & CO. LIMITED,
WOOLWICH, LONDON, S.E.18.
*Member of the A.E.I. Group of Companies*




LAMINATIONS
of all types, in all sizes and in all grades of material.

FERROSIL cold-reduced electrical sheet and strip.

ALPHASIL
cold-reduced oriented electrical sheet and strip.

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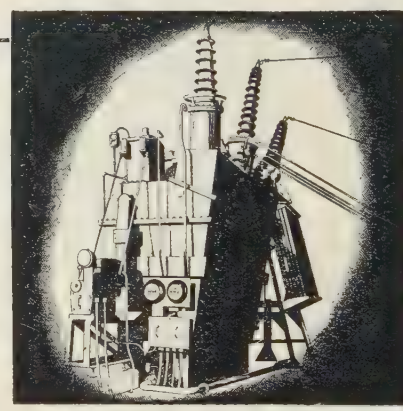
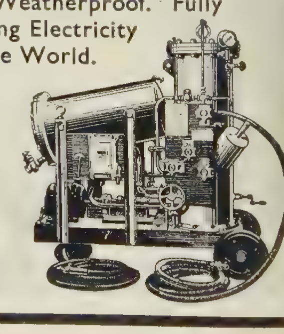
RTB



**TRANSFORMER AND SWITCH OILS**

Complete Drying and Purification giving Maximum Breakdown Voltage in one simple operation. No heating. No fire risk. Weatherproof. Fully mobile units. Used by leading Electricity Undertakings throughout the World.

*Capacities from 20 gallons to 1,000 gallons per hour*



## METAFILTRATION

**THE METAFILTRATION COMPANY LTD.**
**BELGRAVE Rd., HOUNSLOW, MIDDLESEX**
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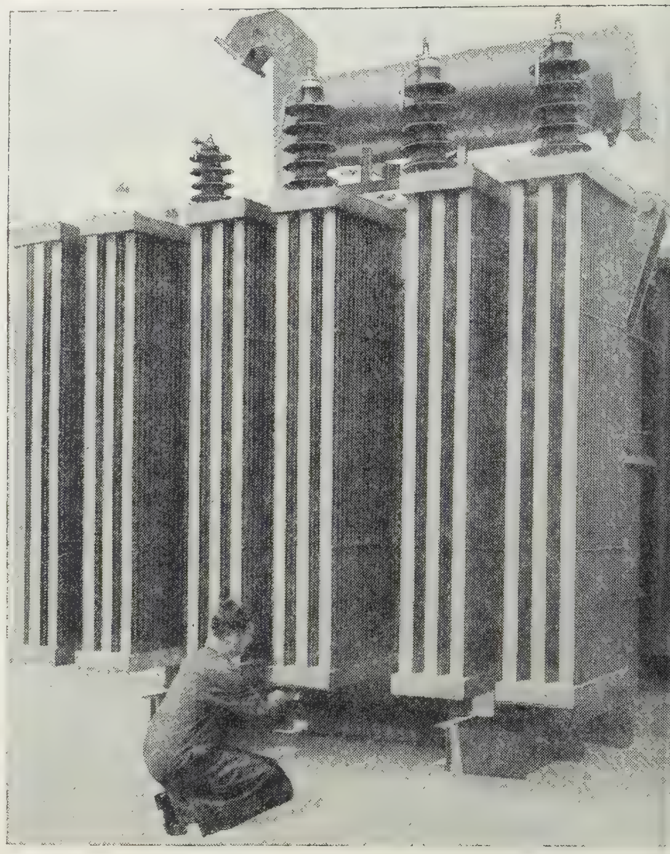
DRAWOUT STEEL TANK
RECTIFIERS
G.E.C.
Easy to INSTALL
INSPECT
MAINTAIN

# SWS POWER TRANSFORMERS



Power and Distribution Transformers in all ranges up to 5,000 kVA and 66,000 volts are manufactured at the Treforest factory.

The Illustration shows a 66,000 volt 2,500 kVA transformer supplied to Pakistan.

S·W·S

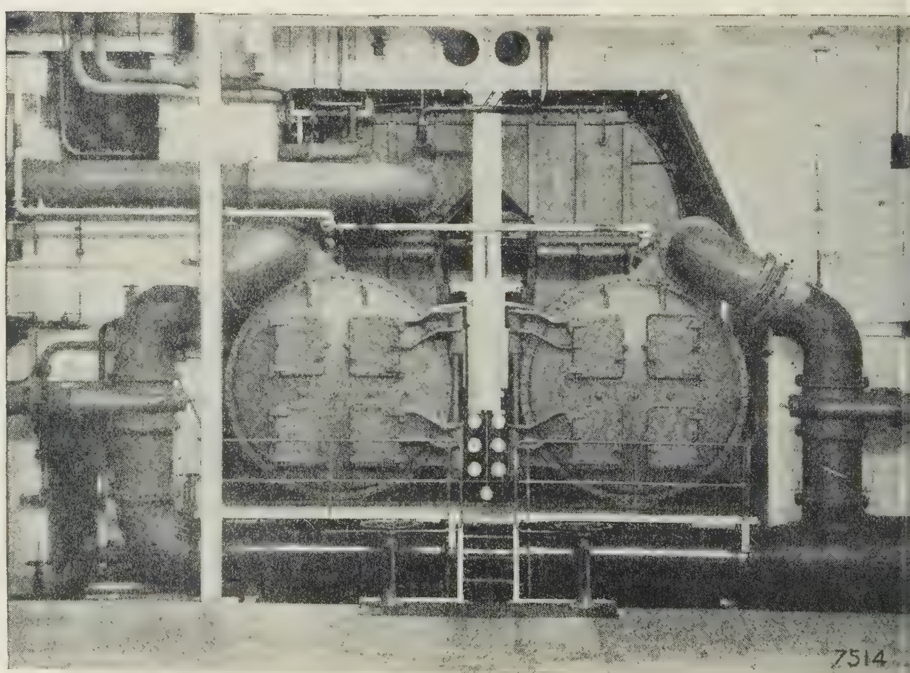
**SOUTH WALES SWITCHGEAR LIMITED** BLACKWOOD · MONMOUTHSHIRE

*Works at TREFOREST and BLACKWOOD.*

---

*Mirrlees*

## *Specialised Equipment* for **POWER STATIONS**




*Photograph by courtesy of B.T.H. Co. Lt*

**Condensing Plant**
**Evaporating Plant**
**Feed Heating Plant**
**De-aerating Plant**
**Pumping Plant**
**Turbines** for auxiliary drives

Illustrated is a MIRRLEES Surface Condensing Plant operating in conjunction with a 25,000 kW Alternator in a South African Power Station.

MIRRLEES Equipment has been supplied for the Power Plants of many Electricity Authorities and Industrial Undertakings in Britain and Overseas.

THE MIRRLEES WATSON COMPANY LIMITED

**SCOTLAND STREET GLASGOW C.5 • MIRRLEES HOUSE 7 GROSVENOR GARDENS LONDON S.W.**


LODGE-COTTRELL
electrostatic precipitators at Bold Power Station
The Electrostatic Precipitators at Bold Power Station are the only means employed for cleaning the Boiler Flue Gases. On official test an efficiency of 98.2% was obtained, the Inlet Dust burden being 6.297 grains/cu. ft. N.T.P.

## THE PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

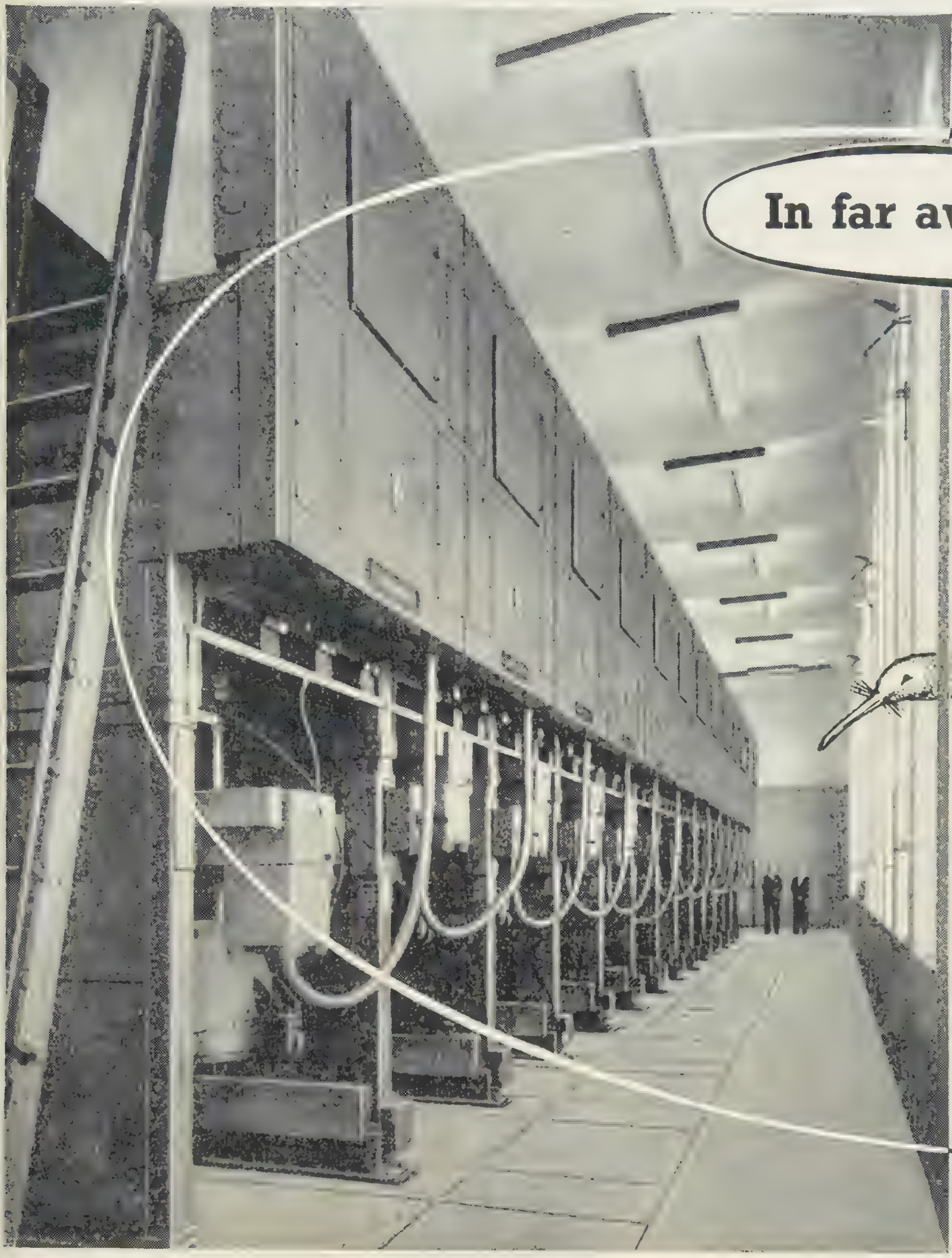
### TEN-YEAR INDEX

### 1942—1951

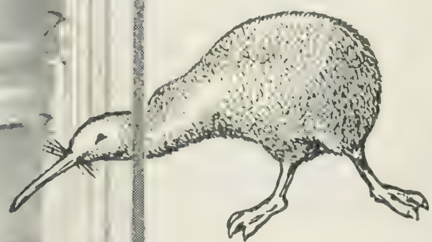
A TEN-YEAR INDEX to the *Journal of The Institution of Electrical Engineers* for the years 1942–48 and the *Proceedings* 1949–51 (vols. 89–98) can be obtained on application to the Secretary.

The published price is £1 5s. 0d. (post free), but any member of The Institution may have a copy at the reduced price of £1 (post free).

## In far away places . . .



*Was the Kiwi impressed?*



**We'll say he was!**

The demand for reliable switchgear of all ratings is continuous. This metalclad switchgear—type VTR13/3—constructed for the State Hydro Electric Department of New Zealand, is a good example of a 1000 MVA—22 kV installation, distributing power to a considerable area in the Dominion. The switchgear incorporates the vertical isolation principle, reducing considerably the floor space required by comparison with that occupied by horizontally isolated types. It is phase-segregated throughout.

Busbar Selection

**Ferguson Pailin** LIMITED *for Switchgear*

Member of the A.E.I. Group of Companies

*Head Office & Works:* **HR. OPENSHAW MANCHESTER 11,** *Telephone* : DROylsden 1301 (Pte.Branch Ex.)

LONDON OFFICE : Bush House, Aldwych, W.C.2 BIRMINGHAM OFFICE Windsor House, 656 Chester Road, Erdington 23 GLASGOW OFFICE : Central Chambers, 109 Hope Street, C.4

*REPRESENTED IN PRINCIPAL OVERSEAS TERRITORIES*

# TYPE D444 STARTER BOARDS GIVE RELIABLE SERVICE

ONE OF TWENTY-SIX STARTER BOARDS INSTALLED IN A LARGE STEEL WORKS

UP TO 300 H.P. 660 VOLTS.
UP TO 200 H.P. 3,300 VOLTS.

| CONTROL | TIERING |
| --- | --- |
| LOCAL | SINGLE |
| REMOTE | DOUBLE |
| SEQUENCE | TREBLE |

M&C S

## M. & C. SWITCHGEAR LTD.

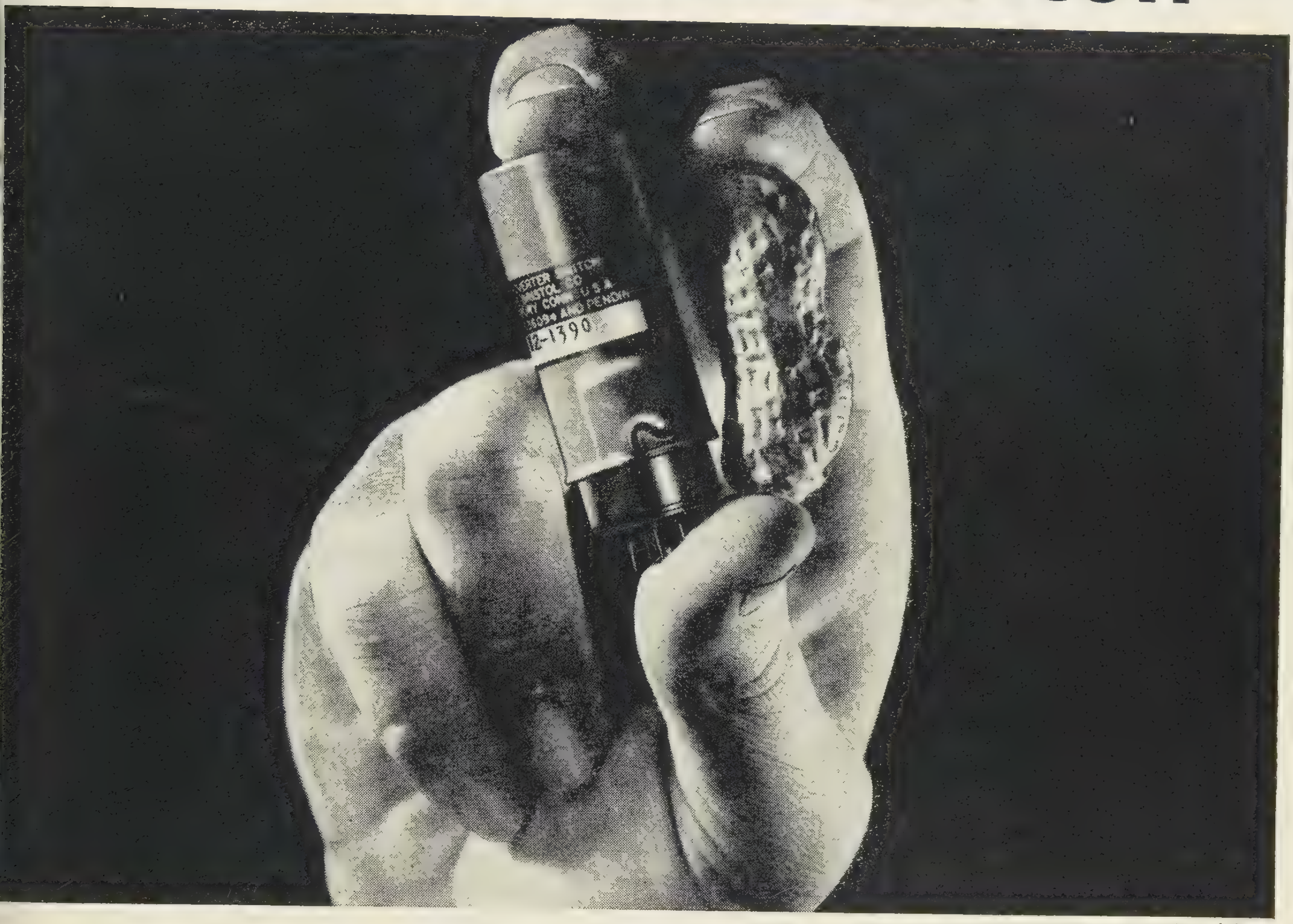
KIRKINTILLOCH GLASGOW

LONDON OFFICE — 36 VICTORIA ST., S.W.1

SHEFFIELD OFFICE — OLIVE GROVE ROAD

BRISTOL'S

# MINIATURE
# Syncroverter Switch



*Actual Size*

## SETS NEW PERFORMANCE STANDARDS

Recently introduced from the United States, Bristol's Miniature Syncroverter Switch is a polarized, single-pole, double-throw, non-resonant chopper providing break-before-make action in synchronism with the current wave of the driving source. Applicable for use over the excitation frequency range of 0-1,800 c.p.s., it converts low power D.C. signals into alternating voltages which can be amplified and applied to electronic, electrical and servo systems. It can be used also as a Precision Synchronous Rectifier. It is outstanding for its reliability, long life, light weight (only ·7 ounces), low noise level and clean wave form.

*Send for full details.*

**TYPICAL OPERATION**

| | 400 c.p.s. | 500 c.p.s. |
|---|---|---|
| Coil voltage | 6·3V. sine, square, pulse wave | 6·3V. sine, square, pulse wave |
| Coil current | 55 milliamperes | 45 milliamperes |
| Coil resistance | 85 ohms | 85 ohms |
| *Phase lag | 55° ± 10° | 65° ± 10° |
| *Dissymmetry | less than 4% | less than 4% |
| Temperature | —55° C. to 100° C. | —55° C. to 100° C. |
| *Switching time | 15° ± 5° | 15° ± 5° |

Mounting—any position—fits 7-pin miniature socket

*These characteristics are based on sine wave excitation

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# ELECTRICAL ENERGY FROM THE WIND

By E. W. GOLDING, M.Sc.Tech., Member.

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SUMMARY

The history of the use of wind power is traced briefly to provide a background to the present renewal of interest in the subject. The characteristics of the wind as a source of power are discussed together with its possibilities for the generation of electrical energy. A short review of the different types of windmill is given leading to a description of the main features of some recent designs. Wind-power research and development work in Great Britain is described with an account of the progress made during the last six years. The economy of wind power on three scales of utilization is dealt with and suggestions are made for making the most effective use of the energy available.

## LIST OF PRINCIPAL SYMBOLS

$V_{AM}$ = Annual mean wind speed.

$V_P$ = Wind speed for full power capacity, or "rated wind speed."

$V_c$ = Wind speed for "cut-in."

$V_F$ = Wind speed at which an aerogenerator is "furled."

$P_c$ = Rated power capacity.

$T_s$ = Specific output in kilowatt-hours per annum per kilowatt.

$C_p$ = Power coefficient, or $\dfrac{\text{power produced by the rotor}}{\text{power in the wind.}}$

$C_{op}$ = Overall power coefficient, or $\dfrac{\text{electrical power output}}{\text{power in the wind.}}$

$\mu_0$ = Tip-speed ratio, or $\dfrac{\text{peripheral speed of the blade tips}}{\text{speed of the wind.}}$

## (1) INTRODUCTION

As civilized man, under the continual urge to improve his standard of living, realized the limitations imposed upon him by the paucity of his power resources as represented by human and animal power, he turned to the natural sources of energy, in the forms of falling water and the wind.

Water mills were apparently developed first and are referred to in Greek and Roman literature. In spite of casual references to very early windmills in Persia, the Middle East and China, no authentic accounts of their use much before the beginning of the Christian era can be found although in "The Pneumatics of Hero of Alexandria" a simple form of the horizontal-axis type of windmill is described. This would place its date about 200 B.C. Ancient remains of Persian mills—of the vertical-axis type and dating from about the 5th century A.D.—have been found, but the sail type of windmill, with a horizontal axis, seems to have appeared in western Europe only in the 12th century and the earliest reference to an English windmill is for the year 1191.

After that date they became increasingly common and, through the efforts of inventors such as Andrew Meikle, Edmund Lee, Stephen Hooper, Sir William Cubitt and John Smeaton—who presented to the Royal Society in 1759 a paper "On the construction and effects of windmill sails"—they reached a high state of development.

At one time some 10 000 windmills were running in Great Britain. They were widely scattered over the country but were commonest in the eastern counties, where they were used for corn grinding and water pumping. Their rotor diameter was often 60–80ft and their power output was 30–40h.p. in a good wind.

While water-mills had to be located close to the water driving them, windmills were built, with a little more freedom in the choice of site, near to their work—hence their frequency of occurrence in the eastern counties of England, which are, in fact, much less windy than the western districts.

With the introduction of the steam engine the windmills met competition which had previously been lacking, and their gradual decline in the 19th century was hastened towards its close by the re-organization of the flour-milling industry on the basis of large milling plants, dealing with vast quantities of imported grain. The fickleness of the wind was always a disadvantage and the specialized workmanship needed to maintain the old-fashioned windmills became less easy to find as the mechanization of industry advanced with the steam engine and, later, with electrification.

As the benefits of electricity became more widely recognized there was a demand for it in remote parts of this and other countries which had then little prospect of receiving a mains supply. Especially in windy districts such as those near our western coasts, on the Canadian prairies and in the United States,

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Mr. Golding is with the Electrical Research Association.

the demand for electric light was met, in part, by the installation of many thousands of small wind-driven d.c. generators of up to some 3kW capacity, operating with a battery for storage to cater for calm spells.

There, in general, the matter rested, but there were some instances of more ambitious developments. In Denmark, following the work of Prof. P. La Cour at the Danish State Testing Station at Askov between the years 1891 and 1908, wind-driven generators of up to 30kW capacity were built. They were applied to various farm purposes and were used as supplementary generating units at the village power stations. These machines, with sail-type rotors, proved useful especially during the two World Wars when oil fuel was difficult to obtain. During the Second World War 88 wind-driven generating plants, some of which were of a new propeller-driven type of up to 70kW capacity, generated more than 18 000MWh for local supply networks in 7½ years.[1]

In Germany also, during the Hitler era, very large designs, some of which are best designated as "fanciful," were put forward. Their sizes ranged up to 20 000kW or more.

An experimental 100kW aero-generator was built by the Russians at Balaclava in 1931. This ran connected to the a.c. network and was intended as a pilot plant for much larger units to be developed by the Central Wind Power Institute established at Moscow soon after the First World War. Since then many smaller machines have been installed in Russia to supply power for agricultural communities.

A 1 250kW aero-generator for use connected to the a.c. network in Central Vermont, United States, was built during the Second World War, and this ran satisfactorily in commercial operation for a short period before the breaking of a propeller blade caused its abandonment.[2] Other design studies for wind-driven machines of 1 500, 6 500 and 7 500kW were made in the United States during the Second World War.[3, 4]

The recent resurgence of interest in wind power generation is due to a number of causes. Among these are the costs of fuels and their high rate of exhaustion in some countries, the need for alternative sources of energy in countries where the end of the exploitation of economic water-power sources is in sight, the desire for independence of imported fuels and the urge to make fuller use of some of the under-developed areas of the world where a mains supply of electricity would be out of the question in the early stages of development.

One can recognize, therefore, three scales in the possible use of wind power: (*a*) small scale, by 0·5 to 10kW sets, for isolated single premises, (*b*) medium scale, by 10 to 100kW plants, for communities which cannot otherwise be supplied economically, and (*c*) large scale, by generators, having a unit capacity of up to 1 500kW or more, used as fuel savers through the energy fed by them into a main network.

## (2) WIND-POWER CHARACTERISTICS

The characteristics of the wind as a source of power, and of annual energy, are considered in Sections 2.1–2.4 with particular reference to the bearing which they have on the operating range of wind speeds to be chosen in the design of wind-driven machines.

### (2.1) The Extraction of Power by a Windmill

The power in a wind stream of cross-section $A$ and moving with velocity $V$ is $\frac{1}{2}(\rho A V)V^2$, or $\frac{1}{2}\rho A V^3$, where $\rho$ is the density of the air. Expressing the power in kilowatts, $A$ in square feet, and $V$ in miles per hour, and using for $\rho$ the standard value of 1 201 g/m³ (at a barometric pressure of 1 000 millibars and 290° K) the formula for the power becomes

$$P = \frac{5}{10^6} A V^3$$

Thus, when the wind speed is 30m.p.h., for example, a windmill rotor of 50ft diameter is met by a column of air the power in which is 265kW. But the rotor cannot extract all this power. Betz, of Gottingen, has shown[5] that the fraction which can be extracted, called the power coefficient, $C_p$, has a maximum value of 16/27 (or 59·3%). Mechanical losses, and those in the generator and control gear, further reduce the power output from the wind-driven machine so that the "overall power coefficient," $C_{op}$, may not greatly exceed 40%. Since the wind is a free source of energy the low power coefficient is not directly important; a reduction of the power output to 40% can be corrected by increasing the rotor diameter in the ratio $\sqrt{(2\cdot 5)}$ : 1. Indirectly, therefore, the effect is to enhance the cost of the windmill because of the larger rotor which is needed. This, together with the initial disadvantage of the low density of the air, constitutes one of the two main difficulties in using wind power economically. The other is the inconstant nature of the wind.

The counterbalancing advantages of wind power are that it is an inexhaustible source of energy which is abundantly available in many parts of the world, and that its utilization, up to the maximum degree which may be feasible, is not likely to be detrimental to the region concerned through the occupation of valuable land or otherwise.

### (2.2) The Behaviour of the Wind

Although, even in very windy places, one cannot rely upon wind at any given time, the variations in the annual average wind speed at a site do not generally exceed ±10% of the long-term mean. Wind is therefore a dependable source of energy but an unreliable source of power.

At sites with an annual average wind speed approaching 30m.p.h. there are sometimes calm periods of several days' duration, while almost windless places have their occasional hurricanes.

The annual average wind speed is the best guide to the energy which may be obtained, and this varies over the world from about 2m.p.h. to 50m.p.h. At most of the places where the economic use of wind power may prove feasible the wind régime, as expressed by the velocity-duration curve (see Fig. 1), takes the same general form with small percentages of calms and of hourly wind speeds above 60m.p.h. When the wind is gusty its instantaneous speed may change 50 to 100% within 0·5sec. Gust speeds do not seem to be related in a direct way to the annual wind speed, so that although gusts of 125m.p.h. were recorded (in January, 1953) at the E.R.A. testing site on Costa Hill, Orkney, where the annual speed is 25m.p.h., gusts of over 90m.p.h. have been measured, for example, at observation stations in India, Australia and South Africa—regions which are normally much less windy than Orkney. The inference is, therefore, that wind-power plants must be designed to withstand high wind pressures no matter where they are to be installed.

It is of interest to examine wind records to determine whether any regular pattern can be recognized in wind behaviour. Taking monthly mean wind speeds first, these may vary from the yearly mean sometimes by as much as 30 or 40%, but very seldom does one find a station which has a reasonably high annual wind speed and yet has some months which are consistently calm. In Great Britain and many other parts of the northern hemisphere January is the windiest month and July and August the least windy.

There is a rather more pronounced pattern in the diurnal variations of wind speed. Thus, at coastal meteorological stations situated on the continental land masses—as, for example, in India or South Africa—throughout the year there are higher wind speeds during the period from noon to early evening, with lower winds during the night. These effects are caused by tem-

perature differences between the land and sea; as the ground warms up there are rising air currents which draw in air from the cooler sea. Land and sea breezes—the former during the night and the latter during the day—may extend to about 10 miles inland in temperate climates, but even 60 miles or more in some tropical regions.

At the sites selected for wind-power studies in Great Britain it is impossible to distinguish any regularity in the diurnal variations; high winds appear as likely to occur during the night as in the daytime. The probable explanation is that diurnal variations are so often masked by storms.

The conclusion to be drawn is that, while in some parts of the world some reliance can be placed on the occurrence of wind each afternoon, in others, such as Great Britain, the wind must be accepted as truly random.

It has been suggested, particularly by Thomas,[6] that some firm power may be obtained through the effect of diversity when wind-driven generators, on widely separated sites, are connected to an extensive network. It is true that the output from a number of interconnected machines is steadier than from a single one, but examination of the wind records from E.R.A. wind-power sites during the past six years shows that a spell of calm weather often covers a large area, so that all the machines would sometimes be out of operation at the same time.

Wind direction is another factor which may have importance in choosing a wind-power site. There is often misconception about the expression "prevailing wind." The direction of this is that direction from which the wind blows for the greatest percentage of the year, but (taking the eight principal directions) this may be only some 15 or 16% as compared with the 12½% which would be the average duration for each direction if the wind were uniformly distributed. There are a few regions, as, for example, the Rhône valley and around Aqaba Bay at the southern end of the Wadi Araba, where the prevailing direction is very marked. At Eilat, on Aqaba Bay, the wind is from the north or north-east for 78% of the year. For such sites there is the possibility of using a non-orienting—and, perhaps, cheaper—windmill without incurring much loss of energy throughout the year.

### (2.3) Annual Energy Output

The annual output of energy from a wind-driven generator of given capacity depends mainly on (*a*) the wind régime at the site, and (*b*) the operating range of wind speeds chosen in designing the machine.

The velocity-duration curve for a site, drawn from an analysis of the measured hourly wind speeds there, gives the number of hours in the year during which the speed equals or exceeds any particular value. Fig. 1 shows the velocity-duration curve for the E.R.A. wind-measuring station at Mynydd Anelog, in Caernarvonshire (annual average wind speed, $V_{AM}$, is 26m.p.h.). The power-duration curve shown is obtained by cubing the ordinates of the velocity-duration curve.

It would be uneconomical to design an aero-generator to operate over the whole range of wind speeds. The machine is designed to cut-in at a low wind speed, $V_c$, at which its output is merely sufficient to supply its own power losses. At the rated wind speed, $V_p$, which is chosen to be some 5–10m.p.h. higher than $V_{AM}$ for the site, the plant produces its full rated power, while for high wind speeds, up to the furling point, $V_F$, when it may be shut down to avoid damage, the output is controlled to the full rated value, $P_c$. The control is by some form of governor, which, in effect, spills the excess power. Referring to Fig. 1, the unshaded area lying under the full-output line and the power-duration curve over the operating range is proportional to the annual output of energy. The specific out-

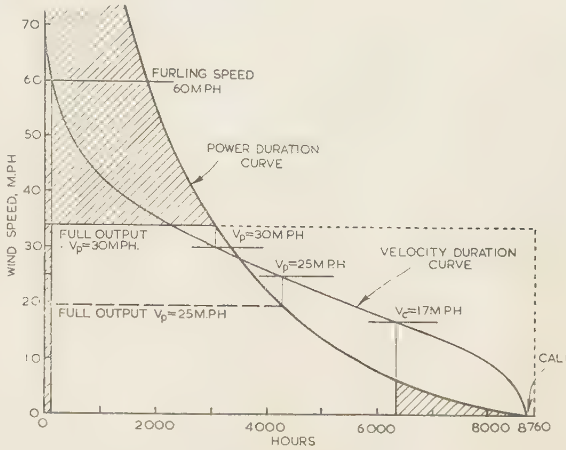



**Fig. 1**.—Velocity- and power-duration curves for a wind-power site.

put, $T_s$, expressed in kilowatt-hours per annum per kilowatt, is the equivalent number of hours at full output. It is obtained by dividing this area by that of the surrounding rectangle (shown broken). Specific output is a function of the shape of the power-duration curve and of the operating range of wind speeds used. It is thus reasonable to speak of the specific output of a site as $x$kWh/year/kW for a rated wind speed of $y$m.p.h.

There is, of course, the implication that the overall power coefficient, $C_{op}$, is constant over the operating range from cut-in to rated wind speed. This is not quite true—since the output is obviously zero at $V_c$—but the power-coefficient/wind-speed curve is flat-topped so that $C_{op}$ does not fall appreciably until the power output is down to about $P_c/3$. The effect of this upon estimates of annual energy output made from wind measurements is therefore usually negligible; this is particularly true at a very windy site when some two-thirds of the annual energy may be given by winds of rated speed or above.

It is probable that the characteristics of the output-controlling mechanism (usually blade-pitch changing) will have a greater effect upon the energy obtained. Power fluctuations in a gusty wind are considerable in magnitude and unpredictably variable in rate. Even with full knowledge of the performance of the controls to be used, the output from a gusty wind may be calculated only with difficulty; without such knowledge precise estimates are impossible. The energy output under gusty conditions will depend on the rate of response of the controls in relation to the fluctuations of wind power, so that the power output of the machine for a given mean wind speed is not quite constant—it will vary with a "gustiness-factor," an agreed definition of which has yet to be found.

The effects mentioned above may, however, be considered rather as of secondary importance. To return to the more important question of choice of the operating range, consider a

**Table 1**

| Operating range | | | Specific output, $T_S$ ($V_{AM}$ = 26 m.p.h.) |
|---|---|---|---|
| Cut-in speed, $V_c$ | Rated wind speed, $V_P$ | Furling speed, $V_F$ | |
| m.p.h. | m.p.h. | m.p.h. | kWh/year/kW |
| 24 | 45 | 60 | 2 000 |
| 21·5 | 40 | 60 | 2 600 |
| 18·5 | 35 | 60 | 3 400 |
| 17 | 30 | 60 | 4 400 |
| 13 | 25 | 60 | 5 500 |

change in this range as indicated on Fig. 1, where the effect of a reduction of $V_p$ from 30 m.p.h. to 25 m.p.h. can be observed. This effect is a great reduction of the annual output of energy from a machine with a given rotor diameter. But this is accompanied by an increase in $T_s$, as represented by the ratio of area under the power curve to the area of the surrounding rectangle. Table 1 shows how $T_S$ varies with the operating range of wind speeds chosen in the design of the machine.

The lower the rated wind speed the higher the specific output but the larger the rotor for a given power capacity. Obviously, from the power formula in Section 2.1,

$$\text{Rotor diameter} \propto \sqrt{\left(\frac{P_c}{\rho V_p^3}\right)}$$

### (2.4) Relationship between Mean Wind Speed and Specific Output

As the work of analysing the wind records from selected measuring sites in Great Britain progressed, it became clear that the velocity-duration curves were all of similar shape, especially over the range which might be employed for wind power. A very important fact thus emerged, namely that $V_{AM}$ for a site could be accepted, for estimation purposes, as a sufficiently accurate—though indirect—measure of the specific output. The curves shown in Fig. 2 were drawn, and almost all the wind régimes so far studied—including those for places abroad—

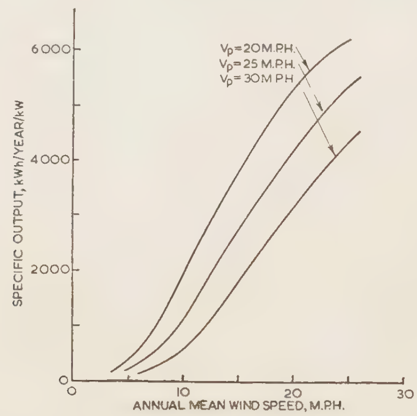



**Fig. 2.**—Relationships between specific outputs and annual mean wind speeds.

conform to them. There may be a few exceptions for stations characterized by unusual percentage durations of very high winds or of calms.

The importance of this for wind survey work is easy to understand; a simple counter instrument measuring run-of-wind, in miles, from which the mean wind speed is easily calculated, can be used for most of the measuring stations, instead of a more complicated and expensive wind-recording equipment giving hourly wind speeds which must subsequently be classified from analysis of the records.

### (3) WIND-DRIVEN MACHINES

To obtain power from the wind one must place in its path a machine which, by retarding it, can extract some of the kinetic energy contained in the passing air. A sailing ship receives its driving power as a simple product of its linear motion, with the wind, and the wind pressure on the sails, but a stationary machine can capture the power only by rotation about an axis which may be vertical or horizontal. Its structure must withstand the full force of the wind because there is no relief, as in the sailing ship, through relative motion.

### (3.1) Types of Windmill

Since the first machine driven by the wind was made, man centuries ago, literally thousands of individual designs mu have been invented. Their number is still growing; some moder inventors are "re-inventing" types which were familiar to th ancient Persians. But all can be placed in one of two mai classes, namely:

(a) *The solid type*, with the effective surfaces of the rotor movi in the direction of the wind.

(b) *The propellor (or wind-wheel) type*, with the rotor rotating a plane perpendicular to the wind.

*The solid type*—machines so called because they interpose co tinuously, in the path of the wind, active rotor surfaces [see Fig. 3(a which almost fill the cross-sectional area of the column of air act on—as distinct from the propellor type, in which only a fraction,

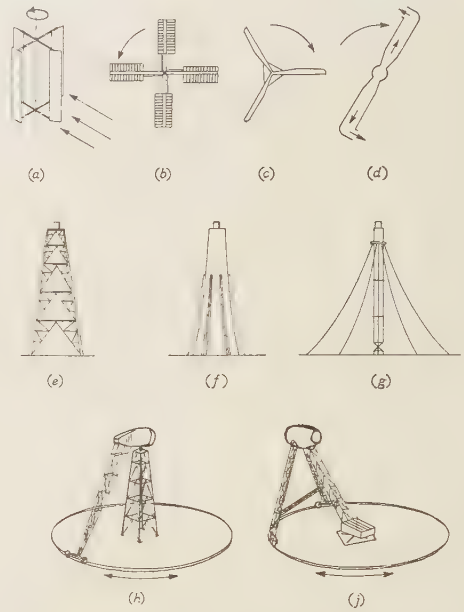



**Fig. 3.**—Features of windmill construction.

$V_p = 30$ m.p.h.

Typical dimensions:

(a) 50 ft high and 20 ft diameter for 10 kW.
(b) 60 ft diameter for 35 kW.
(c) 100 ft diameter for 500 kW.
(d) 80 ft diameter for 100 kW.
(e)–(j) Tower height = ½(dia. of blade circle) + 30 ft.

the swept area is occupied by rotor surface. Another name for th type is the "panemone."[8] A cup anemometer is a simple exampl

Usually, although not necessarily so, they have a vertical ax and the rotor has paddles, or moving vanes, the shape, number an arrangement of which is very variable. They can receive wi from any direction without the need for orientation, but, while t paddles on one side, moving with the wind, are urged forward b it, those on the other side, returning against the wind, are subject to a back pressure unless this is removed by some form of screeni or by turning them edgewise as they meet the wind. The padd surfaces, moving in a circular path, are not all subjected at t same time to the full wind pressure, and there is a screening effe of one on another. It can be shown also that the maximum theor tical power coefficient of a panemone is 0·33 (as compared wi 0·593 for a propellor type of rotor). The actual power coefficie is thus low.

Further, since the active surfaces must always run at a spe lower than that of the wind, the rotational speed—which falls wi increasing rotor diameter—is low so that expensive gearing needed if a high-speed electrical generator is to be driven.

The panemone is not, therefore, a promising type for electric purposes of any appreciable scale, although crudely-construct machines of this type, having a wooden framework and rush ma

for the moving vanes, still serve a useful purpose in pumping water or brine in parts of China and other eastern countries. It has to be borne in mind that efficiency (or power coefficient) is not the main criterion when the input power is free; low initial cost for a machine which operates satisfactorily is the prime requirement, and this can sometimes be met, in small-scale work, by one of the panemone type.

*Propellor type.*—While the active rotor surfaces in the type of machine just described are struck perpendicularly by the relative wind velocity (wind velocity minus the velocity of active surface) those in the propellor type make only a small angle (the angle of attack) with the direction of the relative wind and they rotate at much higher speed [Figs. 3(*b*) and 3(*c*)]. The rotational speed increases as the number of blades is reduced. Two or three blades are used for the high-speed machines generating electricity. The optimum power coefficient is obtained at a value of the "tip-speed ratio"

$$\mu_0 = \frac{\text{peripheral speed of blade tip}}{\text{wind speed}}$$

which varies from about 1 in the slow-running multi-bladed rotor used for water pumping to 2·5 for the old-fashioned 4-bladed windmills, and 6 or more for high-speed aero-generators.

When a wind rotor drives an a.c. generator connected to a constant-frequency network, it must run at constant speed, hence the tip-speed ratio must vary with the wind speed. Optimum power coefficient can then only be maintained (approximately) by variation of the blade pitch, but the cost of control gear needed to vary the pitch with a continually-varying wind speed is probably not justifiable. It may be better to accept the small reduction of power, from this cause, over the operating range of wind speed, and to use pitch-changing—if at all—to control the power output for wind speeds above the rated value $V_p$. The Danish experimental aero-generator of 45 kW capacity installed last year by the South East Zealand Electricity Supply Company,[1] follows this principle; its blade pitch is set to match the most frequent wind speed at the site.

The maximum power coefficient obtainable, in practice, with a high-speed rotor of the propellor type is probably a little over 0·5, which would give an overall power coefficient, $C_{op}$, of approximately 0·4.

### (3.2) Features of Recent Designs

In Table 2 the main features of several designs for large or nedium-scale aero-generators of the propellor type are compared.

It will be observed that the design capacities range from 45 o 7500 kW (with twin rotors) for rotor diameters of 43 to 225 ft nd rated wind speeds of 24·6 to 35 m.p.h. There is agreement n the number of blades as 2 or 3, and variation of blade pitch used in most designs. The S.E.A.S. machine has braced lades with fixed pitch except that the outermost portion of the lade can rotate through 45°, under spring control, so acting s an air brake. Thomas's design[4] with twin rotors also has xed-pitch braced blades, and the rotors, running at variable peed, drive a d.c. generator feeding its output into a convertor.

The generators are most commonly of the induction type, hich is robust and is stable in automatic operation, although utnam[2] used a synchronous generator for the Grandpa's Knob ero-generator, and this type is used also in the Enfield machine.

Another possibility which has been suggested, although so far s the author is aware it has not yet been incorporated in an ero-generator, is an a.c. commutator generator running at ariable speed yet supplying constant frequency.

Smaller blades may be made of solid or laminated wood, but or the larger blades stainless steel and aluminium alloy are e most probable alternatives. For the highest efficiency the lades should have a twist and should taper, but the inner ortions, near the hub, contribute little to the total power, and e higher cost of such blades, as compared with that for ctangular plan-form blades, may not be worth incurring. To lieve the stresses at the roots of the blades under fluctuating ind conditions they may be flexibly mounted so that they can cone" or "drag."

Starting and stopping may be done through a small pilot wind-

Table 2

| Item | Design | Rotor diameter (ft) | Rated wind speed $V_p$ (m.p.h.) | Generator (kW) | Form of rotor | Control of speed or output | Optimum tip speed ratio | Rotational speed of rotor (r.p.m.) | Height of hub above ground (ft) | Method of weather-cocking |
|---|---|---|---|---|---|---|---|---|---|---|
| (i) | Russian (Balaclava) | 98 | 24·6 | 100 (Induction generator) | 3 blades | Variable pitch by flaps | 4·75 | 30 | 76 | Tail vane and electric drive |
| (ii) | P. H. Thomas (United States Federal Power Commission) | 200 | 34 | 7 500 (D.C. converted to a.c.) | Twin, 3-bladed | Speed control through generator field | 9 | Variable maximum 42·75 | 475 | Electric drive |
| (iii) | United States War Production Board | 200 | 30 | 1 500 (Induction generator) | 2 blades | Blade pitch control: electro-mechanical system | 12 | 50 | 150 | — |
| (iv) | Smith-Putnam | 175 | 30 | 1 250 (Synchronous generator) | 2 blades (Rectangular form) | Hydraulic pitch control through fly-ball governor | 6 | 29 | 110 | Yaw vane. Servo-mechanism. Hydraulic yaw motor |
| (v) | Folland (Ministry of Fuel and Power) | 225 | 35 | 3 760 (Induction generator) | 2 blades, 2 stage taper, 11½° twist, fixed coning | Blade pitch control by aileron. Start/stop by pilot windmill | 9·74 | 42·5 | 135 (tripod) | Fantail coupled to bogey wheels through centrifugal clutch on fluid flywheel |
| (vi) | John Brown | 50 | 35 | 100 (Induction generator) | 3 blades, tapered, untwisted. Free to cone and drag | Hydraulic control of blade pitch | 6·5 | 130 | 78 | Automatic electric control |
| (vii) | Enfield Cables | 80 | 30 | 100 (Synchronous generator) | 2 hollow blades | Automatic pitch control by hydraulic system. Variable coning | — | Variable maximum 95·4 | 100 | Self-orienting but assisted by wind-sensitive power control system |
| (viii) | S.E.A.S. (Danish) | 43 | 28 | 45 (Induction generator) | 3 blades | Blade-tip rotation, spring controlled | 5·4 | 56 | 66 | Yawing vane and electric motor drive |

mill which initiates adjustment of the blade pitch according to the predetermined limits of operating wind speeds.

Except in very small fast-running machines, the high rotational speed needed for the generator is attained through gearing. There is usually a gear-box aloft in the nacelle which houses the generator, but some medium-sized machines—such as the Danish Lykkegaard windmills—have a vertical driving shaft running down inside the tower with bevel gears at top and bottom. Alternatives to gearing, which is expensive and may prove a limiting factor in the construction of very large machines, have been proposed. Some large German designs show two contra-rotating propellers, one carrying the rotor of an alternator and the other its stator, but such a scheme would appear to introduce difficulties in operating with an economically short air-gap.

The Andreau principle of pneumatic power transmission [see Fig. 3(*d*)] is interesting. Air is thrown out centrifugally from the blade tips, and the depression created drives an air turbine at the base of the supporting tubular structure. Power losses must be incurred in the double conversion of energy from aerodynamic to mechanical form, at the top and bottom, but there are advantages in having the machinery at ground level and in the lack of any specific relationships needed between the speed of the rotor, the generator and the wind. Rapid changes in torque due to gusts may be damped out.

The form of the supporting structure for windmills is open to considerable variation according to the ideas of the designer. A few possibilities are shown in Figs. 3(*e*), (*f*), (*g*), (*h*) and (*j*). The tripod design of diagram (*h*) has advantages in allowing the head of the aero-generator to be assembled at ground level and then raised, using two limbs of the tripod as shear legs. It also allows the slip rings to be housed in the central building instead of aloft.

## (4) RESEARCH AND DEVELOPMENT

For the successful exploitation of wind power it is necessary to:

(*a*) Find windy sites;
(*b*) Make an aero-generator to operate satisfactorily;
(*c*) Test the performance of the machine;
(*d*) Study the methods of loading to ensure that the available wind energy is fully utilized.

The E.R.A. wind power research programmes have been based upon these four requirements. First, as part of its rural electrification work, and with financial support from the Ministry of Agriculture and Fisheries, research on the small-scale use of wind power for isolated premises was started. This had the twofold object of finding, through performance tests on existing small windmills generating direct current, the most satisfactory one for use in the windy—and often remote—districts of Great Britain, and of determining the best methods of loading to utilize the available wind energy in the fullest possible degree.

Then, as interest in the possibilities of large-scale a.c. generation grew, research on this subject began in 1948 under a newly-established committee on wind-power generation. The initial assumptions[9] were, first, that a number of sites could be found which were windy enough for a specific output of 4000 kWh/year/kW to be obtained from an aero-generator with a rated wind speed of about 30m.p.h., and secondly, that suitable large machines, to be operated automatically when feeding their output direct into main networks, could be built, in quantity, for about £50 per kilowatt.

These two assumptions, if proved to be justified, would make a *prima facie* case for large-scale wind power by leading to an energy cost of 0·25d. per kilowatt-hour—as compared with rather more than 0·4d. per kilowatt-hour for the fuel component of generating cost at coal-fired steam power stations.

The progress made during the first six years is summarized Sections 4.1–4.3.

### (4.1) Wind Surveys and Studies of Wind Structure

Meteorological Office data on wind régimes for observati stations in Great Britain were studied, and analyses were ma to relate them to wind-power possibilities.[10] Following t preliminary work, wind surveys were started in the especia windy western coastal districts. The first were in Orkn Wales and Cornwall, followed by others in Shetland, t Hebrides and West of Scotland and, later, in Northern Irela the Republic of Ireland, the Isle of Man and the Channel Islan In all, more than 100 measuring sites have been used.

These sites have been chosen mainly on the summits of we exposed smoothly-shaped hills without precipitous faces a with no trees or other obstructions to disturb the wind fl over them.

With the valuable aid of local observers, wind measureme have been made by counter-type cup anemometers, mount on 10ft poles and giving the run-of-wind, in miles, at m sites. On others, 30ft poles, carrying electrically-contacting c anemometers and used with specially-built recorders,[11] have be installed. These give hourly wind speeds from which veloci duration curves are plotted. Comparisons are made with t long-term records from local Meteorological Office stations.

At a few sites 70ft masts, carrying anemometers and win direction indicators at different heights, have been used wi photographic and impulse recorders to determine the verti wind gradients over the hill summits.

Located in districts with mean annual wind speeds rangi from 12·5 to 17·5m.p.h., the chosen sites have been found have mean wind speeds of up to 29m.p.h. Out of 65 hill sit of altitudes from 150ft to 2 795ft, 39 have annual mean wi speeds exceeding 20m.p.h., with estimated specific outputs (f $V_p = 30$m.p.h.) from 3 000 to 4 750kWh/year/kW (see Fig. 2)

In the areas surveyed, only representative hills have be selected; doubtless there are many others equally windy.

Experimental studies of the vertical wind gradient ha shown that over a hill summit the mean wind speed increa with height less rapidly than over level ground. Mean hou wind speeds for the highest and lowest points on the circle to swept by a large rotor are not likely to differ by more than 10

Gust anemometers[11,12] have been developed for use with quic response recorders to measure gusts with a 0·1-sec response. balsa-wood windmill-type anemometer, used with an electro counter, has also been built to measure mean wind speeds o periods of a few seconds.

Measurements with these instruments have indicated that:

(*a*) In a gusty wind of mean speed 40m.p.h. the short-peri mean speed may vary between 20 and 84m.p.h. and the rate change of wind speed in a gust may exceed 120m.p.h./s (e.g. 52m.p.h. to 85m.p.h. in ¼sec).

(*b*) The energy contributed by a gusty wind (as calculated cubing short-period mean speeds) is not likely to exceed th calculated from hourly mean speeds by more than 2 or 3%.

(*c*) The vertical component of the wind velocity, affecting aero-generator located on a hill summit, will usually be small.

(*d*) There are periods, of perhaps 10sec, when the distributi of wind speed over the circle swept by a rotor of, say, 6 diameter will be uniform to within ±2m.p.h. This is support by the gust anemometer records shown in Fig. 4. They we obtained from instruments mounted at 110ft, 80ft (at the tw ends of the cross-arm) and 50ft on the rotatable measuring ma at Costa Hill, Orkney (see Fig. 5).

(*e*) At the summit of a roughly conical hill the direction the wind does not influence the preceding statements significant

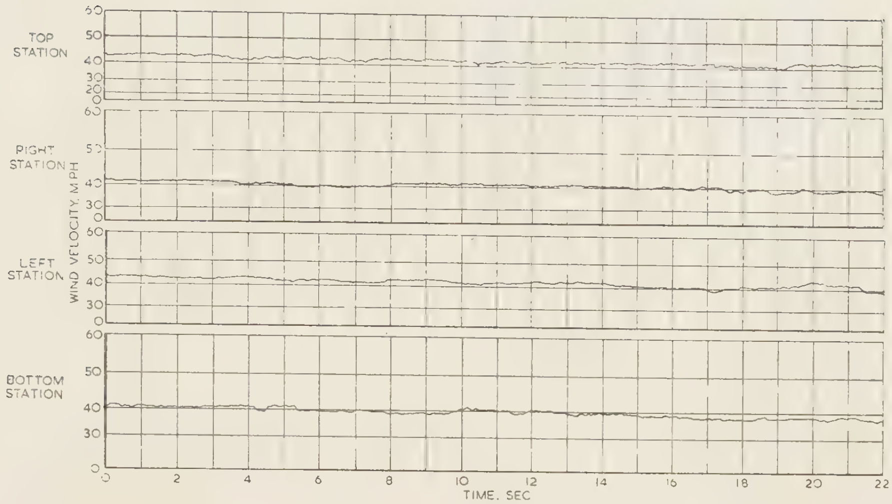



**Fig. 4.**—High-speed records of wind-speed distribution.

In an endeavour to obtain information to guide the selection ' wind-power sites, laboratory work has been done using scale odels of hills in an electrolytic tank. The distribution of ırrent in the conducting solution above the model is taken as ıalogous to wind flow over the hill, but the analogy is by no eans perfect and the useful information to be so gained may rather limited.

(4.2) **Aero-Generator Prototypes and Pilot Plants**

The construction and operation, with an a.c. network, of ind-power plants of significant size lay outside the normal scope ' E.R.A. researches. This important part of the work was ıdertaken by the North of Scotland Hydro-Electric Board and e British Electricity Authority; both placed orders for 100kW ind-driven generators. These are of different types, the main atures of which are given in items (vi) and (vii) (respectively) Table 2.

The first experimental machine was erected during 1951–52 ı Costa Hill, Orkney, and has since been subjected to a number ' trials. There are many difficulties, some of an unexpected ıture, to be overcome in the development of a machine of this nd and in its operation on a very exposed site where the eather conditions are often severe. It is not surprising, there- re, that modifications have had to be made as a result of the ials. These modifications have been connected particularly ith the methods of blade mounting and pitch control. For chnical reasons, also, the blade-circle diameter has been duced from 60 to 50ft, while the rated wind speed has been creased from 30 to 35m.p.h. which is more economical under e wind régime at Costa Hill. Since its erection the structure ıs withstood several very severe gales without damage. The achine has generated its full rated output during test and has en subjected to loads of up to 150kW for short periods. It ıs run in wind speeds up to 70m.p.h. Following the experience ined, its manufacturers are now undertaking the design of a 0kW aero-generator.

The 100kW Andreau-type aero-generator being made for the itish Electricity Authority has been built and subjected to me preliminary trials at St. Albans prior to its installation on final site.

In Denmark, during the same period of development, two achines, the first of 13kW and the second of 45kW capacity em (viii) of Table 2] have been built and tested.[1] These have n satisfactorily for more than 12 months connected to a.c. networks. Their specific outputs have been just under 2000kWh/year/kW at sites with annual mean wind speeds of 11m.p.h.—performances which were rather better than those estimated from wind measurements.

**Fig. 5.**—120ft rotatable mast used for wind measurements on Costa Hill, Orkney.

For use on farms and at isolated premises, two wind-driven machines of 8–10kW capacity have been developed. The first,

with a rotor diameter of 8 metres, is of the Andreau type, and the second, which is now on the market, is a German machine of more conventional design. It has a rotor diameter of 10 metres and produces 8kW in a wind of about 25m.p.h. Tests[13] have been made with this machine driving an induction generator connected to an a.c. network.

### (4.3) Design Studies and Performance Tests

During the past six years a vast amount of information on wind power has been obtained through correspondence and the exchange of visits with engineers abroad, particularly in Denmark, France, the Netherlands and Germany. International co-operation has been organized through a wind-power committee of O.E.E.C.[14] and through the Arid Zone Advisory Committee of UNESCO. More than fifty countries appear to be seriously interested in wind power and several have instituted wind surveys to provide data for the designers of wind-power plant and to serve as a guide to the possibilities of utilizing this form of power.

Many, and very varied, designs have thus come to light, and the need for design and utilization studies has become obvious.

The Ministry of Fuel and Power started to give financial support to wind power development in 1949–50 and put in hand a comprehensive design and costing study to determine the best lines of constructional development to be followed, and also the probable costs of large wind-driven machines.

A suggested design emerged from this study [see Item (v), Table 2] and, based on January, 1951, prices and on the wind régime at Costa Hill, Orkney, a generating cost of rather under 0·2d. per kilowatt-hour was estimated.

The Ministry have also supported E.R.A. work on the testing of the two 100kW pilot plants already referred to. At Costa Hill, Orkney, a rotatable 120ft mast (Fig. 5) carrying gust anemometers and other wind-measuring instruments has been installed, together with electrical instruments to obtain both short- and long-period measurements of output from the aero-generator, corresponding to different wind conditions. A 70ft measuring mast and similar testing equipment have also been provided for tests on the B.E.A. 100kW machine.

In addition, a windmill testing station has been established at Cranfield, Bedfordshire, close to the College of Aeronautics. Here a number of small windmills of different types up to 10kW capacity are being tested in the same wind régime, and a series of investigations will be made to test the effects of artificially-created, irregular conditions of operation. The object is to provide information for aero-generator designers and to test the possibilities of a very simple and cheap construction.

Also at the Cranfield station, in conjunction with tests on small windmills in normal operation at remote premises, studies are being made of the methods of loading best suited to the fullest utilization of the annual energy becoming available. This work is particularly of interest to the Ministry of Agriculture and Fisheries, which support it financially.

## (5) THE ECONOMY OF WIND-POWER UTILIZATION

The cost of energy production by wind power is governed by the annual charges for interest, depreciation and maintenance of the plant, on one hand, and by the annual energy output on the other. The economy can be judged only by comparison of this cost with that for alternative means of energy production. Where electrical energy is cheap, large wind-driven machines must be located at sites with high mean wind-speeds if they are to be competitive, but where generating costs are high, smaller machines and lower wind-speeds may prove economically practicable. Thus the question of economy is relative rather than absolute. It is closely connected, also, with the cost [of] providing storage to cover calm spells. Storage of energy b[y] battery, or by any other means involving the provision of equ[ip]ment which serves no other purpose, is expensive, and, ev[en] when used in only a limited degree, may double or treble t[he] cost of the energy supplied to the load.

Under most circumstances, however, it is important that eve[ry] kilowatt-hour of energy generated by the wind-power plant sh[ould] be utilized. This calls for its acceptance at the random times [of] its occurrence, and if storage is essential it should be by means [of] loads having inherent storage so that no great additional co[sts] are involved in affording it.

The economic possibilities under the three scales of use alrea[dy] mentioned (in Section 1) are discussed in Sections 5.1–5.3.

### (5.1) Small-Scale Utilization

Small wind-driven generators, of perhaps 1 or 2kW capaci[ty] are usually d.c. machines of low voltage—often not more th[an] 32 volts—and are provided with battery storage to cover ca[lm] spells of a few days' duration. Because of the low volta[ge] they must be located close to the premises to be supplied [so] that there is not free choice of site to obtain optimum wi[nd] conditions. The specific output, even in windy districts m[ay] not therefore exceed 1 250kWh/year/kW.

A representative cost, with battery, is £200 per kilowatt, wh[ile] annual capital charges, enhanced by the short life of the batte[ry] may be 15%. This leads to an energy cost of the order of [...] per kilowatt-hour, assuming that the machine is operated [to] make full effective use of the energy generated; probably, [in] practice, a figure of about 9d. per kilowatt-hour would be mo[re] realistic. This cost is high, but, for lighting purposes in a remo[te] district, may not be considered excessive.

A study is being made of the possibilities of using such sm[all] machines, without a battery, for the sole purpose of wa[ter] heating. Matching of the generator and load characteristics [is] then important, but the advantage may be that the need fo[r a] battery is eliminated.

### (5.2) Medium-Scale Utilization

The scope for wind-driven generators in the capacity ran[ge] 10–100 kW is very varied. They may be used on farms or [on] other large premises remote from public electricity supplies, [to] act as fuel savers in supplementing Diesel generation on islan[ds] or in isolated districts where small local networks exist, or [to] act as autonomous, or semi-autonomous, generating plants [to] supply communities which are being established in many of t[he] under-developed areas of the world.[15,16]

In such places the alternatives of bringing in an electric[al] supply from outside the area or of generating by Diesel engi[nes] may, because of the distances and transport costs involved, [be] so high as to be almost prohibitive, yet frequently, especially [on] islands, wind is abundant, so that a sound case can be ma[de] for its exploitation. In assessing the economic possibilities [it] may, in fact, be a question of deciding how low the mean wi[nd] speed can be before the large wind-rotor which it calls [for] involves installation costs—and therefore annual capital char[ges] —which are too high to compete with the admittedly expens[ive] alternative.

There are, as yet, no firm cost data on which to base estima[tes] of the costs of medium-scale plant in general, but evide[nce] from Germany and Denmark on costs for the lower end of [the] capacity range indicates £120 per kilowatt (without batt[ery] storage) as a reasonable figure. Taking 12% annual char[ges] and a specific output of 2 500kWh/year/kW, the generat[ing] cost, for random energy, would be 1·4d. per kilowatt-hour.

Approximate weights and dimensions for wind-dri[ven]

Table 3

| Machine | Capacity | Diameter of blade circle | Tower height | Total weight |
|---|---|---|---|---|
| | kW | ft | ft | tons |
| Conventional type (*a*) .. | 10 | 20 | 45 | 1·1* |
| | 100 | 50 | 80 | 20 |
| Conventional type (*b*) .. | 8 | 33 | 33 | 1·4 |
| Andreau type .. .. | 10 | 28 | 61 | 2·8 |
| | 100 | 80 | 100 | 40·5 |

* Without the tower.

nerators at the upper and lower limits of this range of capacity e given in Table 3.

The economic possibilities of using such medium-scale plant a fuel saver, associated with Diesel generation, are illustrated a curve in Fig. 6 which gives the variation in the costs of wind-generated energy, on this scale, for sites with different annual mean wind speeds. The fuel component for Diesel generation may vary over the range 0·9d./kWh (where fuel prices are normal) to about 3·7d./kWh (at places where heavy transport charges cause the fuel cost to be high). From this curve it appears that the economically usable mean wind speed may be anything from about 10 m.p.h. upwards according to the generating conditions.

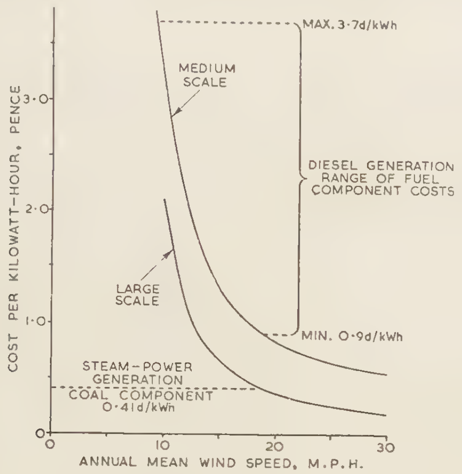



**Fig. 6.**—Curves of energy costs for medium- and large-scale utilization.

The costs for random wind-generated energy in this scale seem reasonably low, but if battery storage is provided to cater for even one-fifth of the annual energy to be supplied through it, the total capital charges will be approximately doubled as will also the total cost per kilowatt-hour of energy. Regarded in another way, the energy supplied through the battery will cost at least six times that for the energy which is supplied direct. The uses to which the output of medium-size machines might be put, with or without storage, are shown in Fig. 7. It might be fed direct into a local network which is supplied from another main energy source, and, in addition or as an alternative, it might be used with one of several forms of storage. Only limited battery storage to supply lighting and other small essential loads would be envisaged. The other loads would usually provide their own storage in chemical (electrolytic), mechanical (water pumping) or thermal form or would be such as could be supplied at random times without calling for storage. There may be scope for the hydrogen-oxygen fuel cell as a means of storing wind-generated energy if a practical and economic form of cell results from present researches on the subject.

In some places where communities are established in under-developed areas having ample sunshine, solar radiation would be combined with wind power, particularly for heating and cooking.[17,18] Another possibility is the use of waste vegetable matter as fuel, for example, in the small steam engine, the development of which has been sponsored by the National Research Development Corporation. Water pumping without the intervention of electricity generation is another obvious and commonly employed means of using wind power.

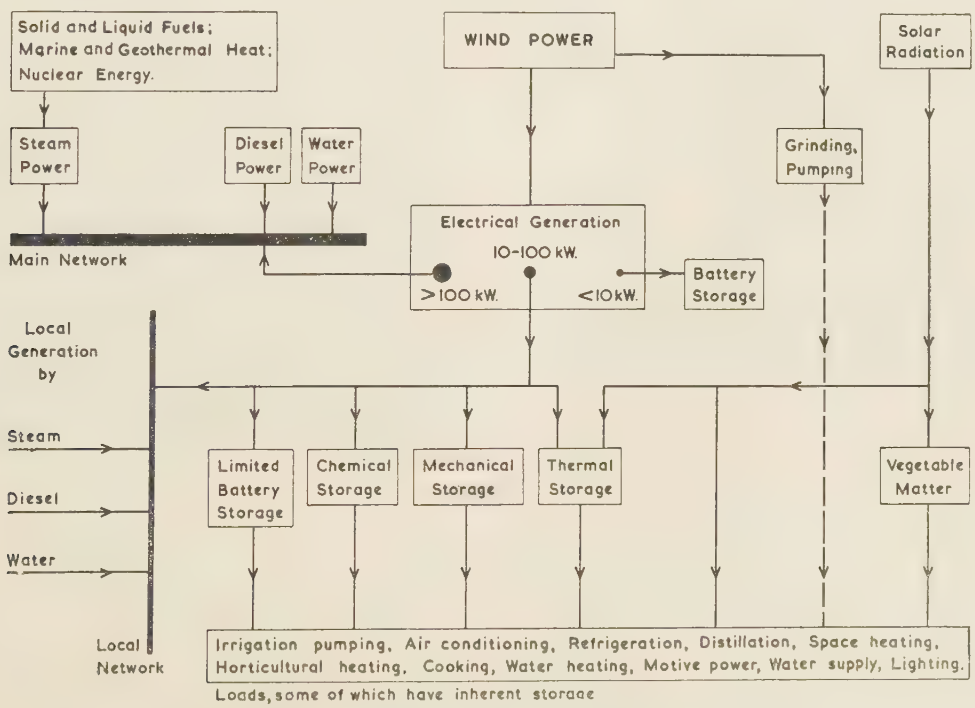



Fig. 7.—The combination of wind power with other power sources.

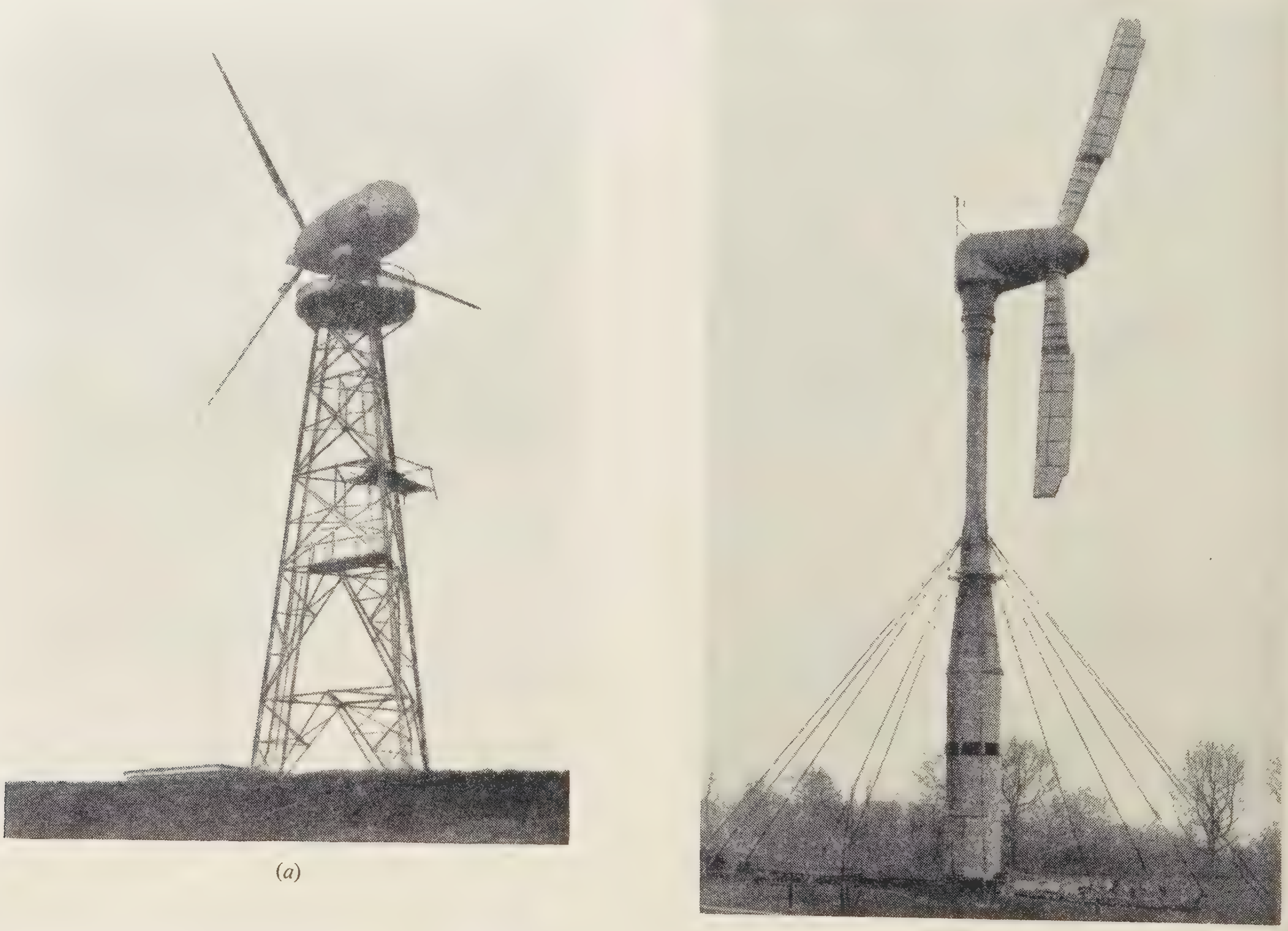
Varied utilization for the loads suggested would doubtless demand some planning to distribute the available energy automatically between them according to a predetermined schedule. Thus, for example, when the batteries for supplying the lighting load were fully charged, the generator output could be used for water pumping. This duty, in turn, could be succeeded by a heating load employing thermal storage. Relays, time switches or other physically-sensitive elements could be used for such control, which would appear to be a fairly straightforward matter from the electrical point of view; the planning of the controls to suit the users' requirements would be more difficult.

### (5.3) Large-Scale Utilization[19–22]

Wind-driven a.c. generators used in connection with main networks have the function of fuel savers. Up to the limit of the minimum power demand on the system—a limit high enough to provide ample scope for wind-power development—the output curve is based on a construction cost of £55 per kilowatt for t wind-power plant (which is thought to be reasonable for t largest size of aero-generator built in quantity) and on annu charges of $8\frac{1}{2}\%$.

In such estimations it is assumed that the network is suf ciently extensive for the output from large aero-generators, unit capacity perhaps between 2 000 and 3 000 kW and built groups, to be picked up without very high transmission cos between the sites and the network.

It is perhaps worth noting that wind power might be combin very satisfactorily with hydro-electric power. The annual energ output from 500 kW of wind-power plant located at a site whe the specific output is 4 000 kWh/year/kW would be equivale to the potential energy of some 200 million cubic feet of wat at 400 ft head. If adequate water storage were available, som firm power value might be allotted to the wind power through th additional hydro-electric generating capacity which might the be installed justifiably.



(*a*) (*b*)

**Fig. 8.**—100 kW wind-driven generators.
(*a*) Generator installed on Costa Hill, Orkney. (*b*) Andreau-type generator at St. Albans, Herts.

can be fed direct into the network to be used without any question of storage. Clearly the cost per kilowatt-hour of the energy so generated must not exceed the fuel component of generating cost by steam. At present this is about 0·41d. per kilowatt-hour in Great Britain, and from the curve in Fig. 6, a mean annual wind-speed of 18 m.p.h. or more at the site would thus be required for economy of wind-power utilization. This

## (6) CONCLUSIONS

To those investigating the possibilities of wind-power utiliz tion it proves a fascinating subject which, admittedly, engende enthusiasm not unmixed with optimism. Within reason, how ever, these are not harmful qualities and there are times, in th pursuit of such an elusive quarry as the wind, when they may b useful. There is much to be done before wind power will b

ble to take its full share in the world's annual production of nergy, but the author and his associates in this work do not e insuperable difficulties in the way. In their view, also, the ontribution which wind power could make to power production, hile certainly limited, is much greater than has been suggested cently by some writers who discuss it as merely an interesting ossibility.

## (7) ACKNOWLEDGMENTS

In conclusion, the author would like to thank the Director of ie Electrical Research Association for permission to present is paper and to express his gratitude to his colleagues who ave played so large a part in the research work which has been escribed.

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## DISCUSSION BEFORE THE INSTITUTION, 31ST MARCH, 1955

**Mr. T. G. N. Haldane:** This is a subject which has excited a eat deal of attention in all countries, and the work which has een done in this country has been of considerable importance. am glad that it has been done in close collaboration and contact ith those engaged on similar work oversea, some of whom we elcome here this evening.

The research work described in the paper has given us a very ll knowledge, at least so far as this country is concerned, of ind velocities, wind structure and the selection of sites. Moreer, in the course of that work there has been an important evelopment of measuring instruments. Some of these have een mounted in very exposed positions on the tops of hills in mote areas, and it was often difficult to erect the instruments d maintain them in operation.

The result of this work is to show that there is a large number sites in this country, chiefly on the western and northern coasts d in the islands, where wind-power plants could be erected and here very considerable power could be generated. That is very tisfactory; but, just because it is so satisfactory, it is all the ore disappointing, I feel, that equal progress has not been ade in the design and construction of large-scale wind-power ants.

In Section 4 the author refers to the original objectives of the research. I should like to emphasize that the principal objective was coal saving. The Wind Power Committee started out to find some means of making a real contribution to the problem of saving coal by feeding into the network the output of large-scale plants. The coal problem is with us even more to-day, perhaps, than it was seven years ago, when this research was started. The fact that it is very much with us is underlined by the remarkable programme of nuclear energy development which has been put in train following the publication recently of the White Paper. It is a very great pity, I feel, that wind power cannot yet be made to play its part in contributing to this urgent necessity to save fuel.

It was originally contemplated that the design and construction and testing of large-scale plants would be a step-by-step process, starting with 100 kW plants and proceeding to 1 000 kW or more. The present position is that we have not as yet completed even the first stage of the 100 kW development. Moreover, we have to reflect that 1 000 kW plants considered in the early days are now beginning to seem rather small compared with the total requirements of the country.

In Section 5 the author refers to the conjunction of wind-power

plants and hydro-electric plants. If we had to-day wind-power plants of, say, 1 000 kW that would permit a very favourable conjunction. The effect of the conjunction would be equivalent to an increase in the catchment area of the hydro-electric system, and there might also be some benefit from a certain amount of diversity between wind flow and rainfall.

Although the position with regard to the development of the large-scale plants is not, I am afraid, satisfactory, there is, as the author has pointed out, very real scope in the medium-scale field. There are isolated communities—few in England, but some in the North of Scotland Hydro-Electric Board's area, and no doubt a very considerable number abroad—where medium-scale plants may be extremely valuable. The problem of designing such plants is obviously easier than the design of large plants, I believe there is no fundamental reason why satisfactory large-scale plants should not be produced if sufficient time and money are devoted to the problem. Although this problem could, I think, be solved, we are faced with the fact that the magnitude of the problem is increasing as time goes on. Seven years ago 1 000 kW may have been a good target figure, but I doubt whether it is sufficient to-day.

I am dubious of the possibility of developing wind power satisfactorily by large numbers of small plants; I think that the operating and other difficulties involved would be very considerable. I am glad, however, that the author draws attention to the fact that there are some complications in the 100 kW plants, particularly with regard to pitch changing, etc., which might be eliminated, and this might make the problem of developing large-scale plant a little less difficult.

In conclusion, I should like to say that I think the future of large-scale wind power—and it is with large-scale wind power that I have been chiefly concerned—depends entirely on whether or not we can succeed in designing and building large-scale plants. If they can be built, there is no doubt that there are sites available at which very large outputs of energy could be obtained.

**Prof. D. Dresden** (*Netherlands*): In Section 2.2 of the paper the author says: "Gust speeds do not seem to be related in a direct way to the annual wind speed, so that although gusts of 125 m.p.h. were recorded (in January, 1953) at the E.R.A. testing site on Costa Hill, Orkney, where the annual speed is 25 m.p.h., gusts of over 90 m.p.h. have been measured, for example, at observation stations in India, Australia and South Africa—regions which are normally much less windy than Orkney."

The inference—and this is where my criticism arises—is therefore that wind-power plants no matter where they are to be installed must be designed to withstand high wind pressures. This statement is wise, but there is still a great difference between the force exerted by a 125 m.p.h. wind and the force exerted by a 90 mp.h. wind. Those figures of 125 and 90 are misleading, because the force exerted by the wind speed is, as is well known, more or less proportional to the square of the speed, so that we have to compare $125^2$ with $90^2$. That means that the force in the former case is considerably higher than in the latter. This again means that in regions where exceptionally high speeds of 125 m.p.h. may occur the first cost of erecting the structure will be considerably higher; and, as the main item in the cost of electricity generated by wind is the first cost, it is very important to try to find the maximum wind speed which is not entirely certain to occur but more or less probable. Even in places where it may be supposed that the wind speed will never be more than 90 m.p.h. it may happen that at some unforeseeable time in the future a higher wind speed will occur, and in such a case the station will suffer; but no architect builds a house to withstand wind thrusts which have never been known to occur in the country in which he is building it, and, if such a calamity does occur, no one will blame the architect if the house is wrecked. It will be necessary to determine as far as possible how stro[ng] a wind will, once in so many years, occur on a certain site.

My second point of detail occurs in the last paragraph [of] Section 2.2, where the author says: "There is often misconceptio[n] about the expression 'prevailing wind.' The direction of this [is] that direction from which the wind blows for the greatest pe[r]centage of the year, but (taking the eight principal direction[s]) this may be only some 15 or 16% as compared with the $12\frac{1}{2}$[%] which would be the average duration for each direction if t[he] wind were uniformly distributed."

This is probably true, but may be misleading, because t[he] decision whether or not a non-shifting installation should [be] chosen depends not entirely on the frequency of this wind dire[c]tion but on the contribution which this wind makes to the annu[al] energy, and it is necessary, in addition to the direction of t[he] wind, to note in some way or other the force, and the wind spee[d]. The "prevailing wind" in my opinion is the most important o[ne] from the point of view of yearly available energy.

In this respect it may be of interest to mention that wi[nd] measurements in Holland are being carried out at two height[s]. Near the shore we have a radio tower and we have wind-spee[d] measurements at 35 ft and at 225–250 ft. We measure the wi[nd] speed in the same way as the author does and add the direction [of] the wind. All the data available are punched on cards, and t[he] cards are dealt with in our statistical department, so that it [is] simple for us to refer at once to a certain hour of the day, [a] certain wind direction, a certain wind speed and so on. One [of] the data which we think is important concerns the direction [of] the wind. It may be shown that the greater part of the year['s] available energy comes from a certain direction which may app[ly] only for 15, 20—or even 10% of the time, if this wind is fa[r] stronger than the others. On these cards we punch the wi[nd] speeds, and it is easy in our statistical department to work o[ut] from the wind speeds the cube root of the average cube value [of] the wind speed, so that in a simple way we obtain the mo[re] important average of the cube value instead of the average valu[e] itself. The mention of these details does not imply any seve[re] criticism of the paper.

In the Conclusions, the author says that to those investigati[ng] the possibilities of wind-power utilization it proves a fascinati[ng] subject which, admittedly, engenders enthusiasm not unmixe[d] with optimism. He goes on to say that within reason these a[re] not harmful qualities.

I think that he is far too modest on this point. To predict t[he] future of wind power is, of course, just as difficult as to ma[ke] any other prophecy, but it is a matter of experience that mo[re] prophecies made by real prophets have come true than is to b[e] expected from mere chance. The explanation is that tho[se] prophets not only make predictions but inspire enthusiasm, a[nd] their followers, believing in the prophecy, by their work a[nd] action help to realize it. That is why so many of these propheci[es] come true, because people believe them and act accordingly a[nd] so themselves make true what was originally only an idea.

**Mr. W. T. J. Atkins:** The recent revival of interest in wi[nd] power in this country has been mainly fostered by the author a[nd] his colleagues at the E.R.A. The B.E.A. decided some fo[ur] years ago that it was their duty to support this cause, main[ly] through their need to search for alternative power resources [in] view of the falling trend of national coal supplies.

The paper mentions two inherent handicaps of large win[d]-driven plants, one being their huge bulk in relation to rating a[nd] the other their dependence on the supply of wind. It seems tha[t] a third difficulty must now be added, and one which was no[t] foreseen by either the E.R.A. or the B.E.A.—namely, publ[ic] opposition on the grounds of size and allegedly unattracti[ve] appearance. These are bound up with the necessity of placi[ng]

a windmill on something of an eminence, where it inevitably dominates its surroundings. As a result of this opposition, the B.E.A. have so far been unable to use the Caernarvonshire site for which the machine built for them was designed; consequently that machine still remains at a temporary site which was used for trial erection purposes near the manufacturer's works, and it seems likely to stay there indefinitely. A certain small amount of running has taken place, but anything like serious operation is quite impossible on such an inadequate site, which is situated in the Home Counties and is badly screened by trees. To make matters worse there has been an abnormal prevalence of anti-cyclonic weather in the first quarter of this year.

On the question of aesthetics it may be that future development will lead to windmills assuming what are regarded as more pleasing forms, just as the aeroplane has grown from a "stick and string" contraption to an object of some beauty. Perhaps also a different verdict might have been forthcoming had the experts consulted been more judiciously chosen for their advanced views.

Section 5 deals with economics, and in comparing the cost of a wind-power plant with a steam-power station, the fuel component is used as the yardstick. This is misleading, however, if other costs are not equal. Taking rough figures from some recent B.E.A. reports, operation, repairs and maintenance in an average steam station amount to 0·075d. per unit with a man-power of 2·25 generation employees per 1 000 kW. I should expect the corresponding figures for wind-power plant to be much higher.

The author mentions the difficulty of getting information on air flow as influenced by topography and seems doubtful of the validity of his electrolytic-tank experiments. Has he considered the use of a technique which has been developed in the B.E.A. Research Laboratories for studying this kind of problem? In this method, small balloons, inflated to have a nicely adjusted degree of levitation, are released, and their subsequent motions are observed in order to indicate the air-velocity variations.

**Mr. J. Juul** (*Denmark*): The author has proved wind power to embody vast amounts of energy which will meet a material part of the steadily increasing demand for energy, if stable and reliable wind-power plants can be constructed at a suitable cost.

As mentioned by the author, we have had a couple of experimental plants running in Denmark for a few years and are now constructing a third pilot plant of 200 kW. Our experiments have shown it to be technically possible to supply our network with wind energy transformed into 3-phase alternating power, thus achieving such savings of coal in our thermal power stations as to create an economically sound basis for the erection of wind-power plants to a larger extent. How such wind-power plants should be devised is the standing question; it will undoubtedly be worth while making considerable efforts towards finding the correct answer.

In the electricity industry it has become a habit to take it for granted that a modern power plant must needs be a big unit with machines of 100 MW or more. This is first and foremost due to the fact that considerations regarding the most economical utilization of fuel make it necessary to use large units with appurtenant expensive main lines and a widely ramified network for distribution of energy to a great many relatively small consumers.

The utilization of wind power in correspondingly large wind-power plants will hardly be technically feasible, seeing that the energy of the wind appears in the shape of kinetic energy in such light-weight matter as air. As I see it, it will therefore be necessary to become familiar with the idea of utilizing the energy of the wind by means of a large number of automatically working units, small in comparison with steam power plants, and placed with advantage on windy sites along the widely ramified network of supply.

I think there are absolutely no drawbacks in using numerous small wind-power plants, but it is, on the contrary, a great advantage that these units can produce cheap electricity, though being fairly small. When using many small plants it is possible, by gradual erection of more units according to need, to increase the power production evenly and steadily, and possible defects or failure to produce, in the case of one or a few of the small plants, will not have the same dire consequences as failing production in a large-size thermal power station.

I believe that, if scientific research and modern technique of production are applied, it will be possible to build wind-power plants in such a manner that they will be able to produce a material part of the power needed and do it economically and profitably.

There is at present much talk of utilization of atomic energy and there is every reason to look forward to the use of this source of energy, as well, for the production of electricity. I do not think, however, that atomic power plants will render the use of wind energy superfluous. We shall surely need all the energy that can be used with advantage, and it is worth while to remember that wind power is actually natural atomic energy, it being produced by heat from the sun, which is Nature's great nuclear reactor.

**Dr. R. Frith:** Some time ago I made an analysis of the variability of daily wind means from day to day, of hourly means from hour to hour, of yearly means from year to year and so on. The analysis, which covered a very wide range of time intervals, ranging from a few seconds to a few years, was made in this way. I took, for example, a long series of observations of daily means and noted the difference between the highest daily mean and the lowest daily mean in every set of consecutive five days. The mean value of these differences was then expressed as a percentage of the mean wind over the whole period and used as a measure of the variability of the daily means. A similar analysis was carried out for all other time intervals.

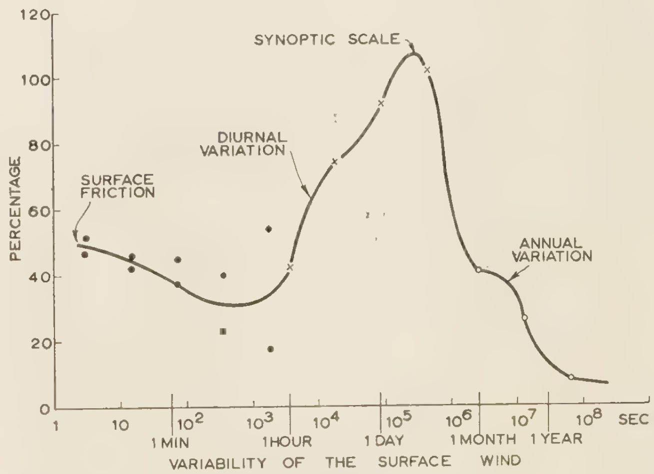


Fig. A

Fig. A shows the curve which I obtained. The points marked by crosses and circles are all from very long sequences of observations and are reliable. For the shorter periods two special runs, each lasting 24 hours, were made with a rapid-response anemometer. The results, shown by the two sets of dots, were very different, and the run of the curve to the left of the last cross is rather a matter of guesswork.

The general shape is much what we should expect. Surface friction gives rise to fluctuations which go up and down in a few seconds. Then there is a peak at round about $3\frac{1}{2}$ days corresponding to the variations of wind due to the passage of depressions and anticyclones; and we then drop down to the small variation from year to year.

I do not know what the importance of this curve is from the point of view of wind power, but it does indicate the sort of variations of energy output that are likely over different periods.

**Mr. T. Mensforth:** The organization with which I am associated decided to develop large-scale generators, i.e. 100 kW or more, suitable for scaling up to the largest sizes. In 1950, when the design was made, we lacked windmill experience and the purchaser wished no delay. There was scarcity of materials and labour; existing proprietary parts were adapted; manufacturing commenced before the project design was complete, so causing troubles later.

Progress has been slow, owing to formidable difficulties, including unsuitability of the site (Orkney) for a first large experimental machine (owing to inaccessibility), lack of workshop facilities, snow, icing of high-voltage lines, salt corrosion, humidity, etc., vibration and resonance of hub and blade system, hunting of governor due to inability to meet exceptionally exacting requirements, tower resonance, electrical insulation troubles, ingress of moisture to proprietary densified-wood blades, and hardship and sickness from exposure.

Much has been learned from indispensable hard-won experience. 250 kW machines and scaled-up larger versions can now be designed with reasonable confidence and differing materially from Orkney, namely two blades with rocking yoke instead of three hinged blades, a rigid blade system probably being impracticable because of stresses due to gusts; blade to ground clearance about 25 ft or rather more for largest sizes; as high towers offer little advantage on hill-top sites; rigid tower, as blade erection need not be difficult and collapsible towers are not justified; induction generator mounted aloft; electric motor for yawing as fantails are not economic; suitable governor unit now developed and bench-tested; hydraulic blade-pitch control in preference to other systems; tower slip-rings for main supply circuits only.

I consider £55 per kilowatt optimistic, our estimates for the 250 kW project being much higher, although I believe wind power can be economically attractive. Small and large windmills of the same type can, as regards mechanical parts including blades, be geometrically similar. Power is therefore proportional to swept area, i.e. to square of dimensions; weight is proportional to their cube. This weight penalty is fortunately counterbalanced up to an optimum size of perhaps 1 500 kW, since the weight and cost of the electrics, control gear, etc., do not increase so rapidly and the tower height need not rise in proportion to the blade diameter.

I feel that sizes above 250 kW will not offer outstandingly increased economies, and advocate the cautious policy of first developing units of, say, 250 kW, and then perhaps 600 kW, before attempting the very largest machines, since the technical problems and hazards increase rapidly with size.

**Dr. U. Hütter** (*Germany*): Speaking as a designer I agree with every point in the paper and with all the ideas and facts which it contains. The idea of using the energy of the wind through the generation of electricity is getting beyond the stage of the first uncertain steps of preliminary tests. This is demonstrated by the fact that many countries have established organizations to study the problems of using the power of the wind.

In Germany, the approach to the use of wind energy was not made by making wind surveys first, but by designing, constructing and testing machines of a certain size. These machines varied in diameter from 30 ft to 60 ft and in output from 6 kW to 50 kW.

At present the tendency in Germany is towards the development of automatic working machines with a high "rated speed" —the relation between the speed of the blade-tips and the velocity of the wind at the moment of operation of the machine. I think that this figure is one of the most important factors in keeping a machine to a low price.

A high rated speed entails a small gear that means a low weight and thus a low cost of machine. As the cost of the machine is the biggest part of the cost of the energy, the cost of the energy will be as low as possible.

As a result of many studies, there are a number of machines on the market, one of which, made by the organization with which I am associated, the author has had the courtesy to illustrate this evening; it is under test at Cranfield. We have already supplied about 60 of these machines to a number of countries, and 34 operate in Germany. (See Fig. B.)

**Fig. B.**—Wind-driven plants installed near Papenburg am Ems.

As the high costs of development work should not fall only on the shoulders of private persons and industrial groups, there was founded in Germany, in 1949, an organization similar to those which exist in certain other countries, namely the "Studiengesellschaft Windkraft" in Stuttgart, which has as members all the groups that are particularly interested in wind power. The targets which it has set itself are to get wind surveys for Germany, and to design, construct and test a machine of 100 kW output.

The study of the records accumulated over many years by the meteorological stations in Germany, and their evaluation, has shown the distribution of wind velocity over the whole country.

We hope to link up the evaluated isovents with neighbouring countries, so that we may have a picture of the wind velocities over a large part of Europe, and, as distant a target, of the whole world. The choice of sites on smoothly-shaped hills free of obstructions, to which the author refers, is a very good plan, as we have seen from a special study on the influence of the surface roughness on the average velocities of the wind. If we take a section from the sea to the mountains in the south of the country, showing the velocity distribution of the wind with height and distance, it seems that there is a similarity with the velocity distribution in the boundary layer of a rough surface. That means that every high point which comes into higher regions of this boundary layer comes into a velocity which is much higher than the average velocity over the average surface (see Fig. C).

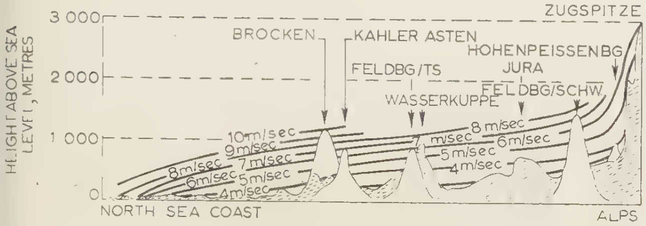


Fig. C

To achieve its second target there has been a technical competition open to everyone in Germany. Our group of designers won this competition, and now we are designing this machine. We hope that it will be possible to begin the construction of the machine at the beginning of 1956 and to start the tests at the end of that year.

In the meantime, we have solved the task of using wind power for a pumping station of about 60 kW, and for this we connected eight wind-power machines of 8 kW together to feed the motors which drive the propeller-type pump. This installation has been running for more than a year and is operating satisfactorily. There are no difficulties in running these eight machines in parallel. This is an important fact, because it means that, if we want a 1 000 kW unit and have a satisfactory 100 kW machine, we have only to put ten of these on a windy site to constitute a 1 000 kW unit. That has the advantage that it is only necessary to develop a satisfactory 100 kW unit, which could be constructed by mass-production methods. There is reason, therefore, for a certain optimism about the possibilities of using wind-power plants even up to the size of output which the electricity authorities will consider suitable.

**Mr. A. Argand** (*France*): Our application research in France for the last few years has been on lines parallel to those in Great Britain. In Metropolitan France about 140 sites have been prospected; anemometers (the indications of which are independent of wind direction) have been placed on existing supports (broadcasting aerials, lighthouses, towers, bell-towers) or on semi-light pylons specially erected for this purpose. These anemometers are connected electrically to meters set near the ground so as to be more easily accessible. Every 14 days readings of the meters are made everywhere at the same time, enabling us to study the space correlations. Except in the south-east, with rather local régimes, a really river-like wind blows across four-fifths of France.

Speaking only of the regions not much exposed to frost, the Pas-de-Calais, Cotentin, Finistère, Roussillon, the Rhone delta and Corsica show at certain points, and annually, theoretically recoverable power exceeding 3 500 kWh in a swept area of 1 $m^2$ at a height of 40 m above ground. Some units of this type have been installed in Scotland, England, Denmark, Belgium, Spain and Brazil, enabling us to make interesting comparisons with anemometers used in these countries.

In other parts of the French Union similar investigations have been launched. In certain parts of North Africa, and more particularly in Tunisia and Mauritania, encouraging results have been obtained, provided that the winds do not convey too much abrasive sand. Generally the regions near the equator—Djibouti, French Equatorial Africa, Dahomey, the Ivory Coast, Martinique, Guadeloupe and Guiana—have given disappointing results, whereas Saint-Pierre, Miquelon, and especially the Kerguelen Islands, appear to be swept by powerful as well as steady winds.

Thus, available powers in the ratio varying from 1 to 200 and even more can be found among sites generally considered as windy by the local authorities. This considerably limits the places where large wind-generators of 1 000 kW and more will have to be erected if one day they become profitable. In addition, these will have to supply a widely-interconnected network and they will only be able to feed into it an auxiliary power which is very unsteady over a period of one hour or even one minute.

It seems, indeed, that at the present time we do not know how to store, at a non-prohibitive cost, an adequate quantity of power, and so regularize the output of wind-generators even if they do not exceed 20 or 30 installed kilowatts. It has indeed been suggested that they should be coupled with regularizing units—heat engines for examples—without electric storage batteries in parallel, but so far as we know nothing of this kind has been perfected.

Our models for tests in wind-tunnels or natural wind have up to now been far more reduced in scale than the British ones; they range from a few hundred watts to a few kilowatts, and the tests which we have made on structural elements of future large units have been merely static tests such as are used for aeroplanes. Such problems are difficult to solve but do not seem to be insoluble.

We think, however, that provided they are cleared of surrounding obstacles and made sufficiently large, there are but few regions where the use of individual small wind-turbines would be impossible for technical reasons, owing to continuous lack of wind. These machines are the only ones which are really perfected at the present time. The capacity of their electrical storage batteries, however, has to be fairly large, and therefore very expensive, because nearly everywhere periods of many hours, and even days or weeks, may pass without the power supplied by the driven generator being important in relation to the installed power.

Another interesting use of low-power wind-turbines appears to be the supplying of lighthouses. These are well adapted for producing this kind of power, because they form a natural, strong and unobstructed support and are almost always continuously looked after by qualified persons who have already large electric storage batteries at their disposal.

**Mr. H. Munro:** Internationally there is fairly general agreement on the nature of the question of wind-power development, on the problems to be solved and on the way and the order in which those problems should be solved.

In the Republic of Ireland the only concern is with large-scale utilization, i.e. wind-power utilization to feed networks, since, owing to the size of the rural network, there are very few isolated loads left.

I question the author's figure of 0·41d./kWh as the incremental cost of the fuel-generated electricity against which wind power has to compete; I feel that this price is rather low. Wind-generated electricity should be regarded as a negative consump-

tion on the network rather than a positive contribution to the system load. The effect of wind generation is to reduce the load on those stations which normally carry the fluctuations in the system load. These are the less-efficient stations whose incremental fuel costs are higher than 0·41d./kWh.

Up to a certain extent wind power can be regarded as firm power. The effect of high wind is to produce an increase in the system load just as cloud, rain and sun produce alterations in the system load. If there are wind-power plants on the system they would work to cancel out the alterations in system load due to wind. Wind power can therefore be regarded as firm power up to the amount by which wind increases the system load. How much that could be I do not know, but it could hardly be less than 100 MW, so that in Great Britain at least the first 100 MW of wind-power plant would replace firm steam-power plant, which could cost £50–£60 per kilowatt, as well as making an energy contribution which would be worth a further £55 per kilowatt.

The Ministry of Fuel and Power had chosen 3 760 kW as the best size for a wind generator. I think that ten 100 kW windmills would be practically as cheap as one 1 000 kW machine. What is needed for wind-power development at this stage is to have a simple and reliable wind generator of 100–400 kW designed, built and run. This would be a practical aim rather than to think in terms of larger sizes.

**Mr. C. A. Cameron Brown:** As a result of my intimate experiences with wind-generating plant in the early 1920's I came to two very firm conclusions. One was to the effect that the structural design of wind-power plants at that period was not good enough to put a really reliable machine in the hands of would-be users. And the second was that, owing to the use of storage batteries which could not possibly be large enough to make a full utilization of the wind, the net cost of the energy generated would be high.

When taking this matter up 20 years later at the E.R.A., I proceeded from that point to formulate a hope that modern materials and construction could substantially improve the first factor and that by devising means of storage other than batteries a better utilization of the wind would be practicable. In this better utilization I envisaged storage steam raising, storage water heating, storage cooking and any other thermal method of making full use of the energy available at periods of the day when immediate consumption was not otherwise practicable.

I have no particular interest in the very large mills but I am firmly convinced that there is a tremendous field for development of the smaller mills of 5–10 kW capacity. A mill of this size within a wind characteristic of 3 000 kWh/kW could be expected to provide a net availability of anything up to 30 000 kWh per annum. This, of course, would give an excellent electrical service to a number of farms or a farm and a group of houses, or a small residential community. All that is required is (*a*) a reliable machine, which it should now be within our powers to produce, and (*b*) a method of making a fuller utilization of the wind availability in which connection the storage method coupled with a certain amount of battery capacity would appear to hold considerable promise.

Also, I should like to mention a fact which is omitted from the historical introduction to the paper. The first recognition of the possibilities of using wind power for the generation of electricity was made not by the E.R.A. or by the electrical industry but by the Ministry of Agriculture and Fisheries, which in 1923 threw open to the world an invitation to send the best that they had in electrical wind generators for test in this country. Scores of manufacturers from all over the world showed an interest, and about ten makes were eventually submitted. The standard of work and the methods of test were not in the same high category as the work of the E.R.A., but it was a step forward and should be on record.

**Mr. J. Fonquernie** (*France*): In France too an engineer has discovered the principle to which the author refers in Section 3.2, where he says that air is thrown out centrifugally from the blade tips and the depression created drives an air turbine. There has been founded in France a society having the same ideas as the author, and it is devoting all its efforts to the perfection of this "depression" method, as the author calls it. This type of generator is illustrated in Fig. 8(*b*).

There should be great scope for using wind energy in the countries of Africa and Asia, and also in the United States, where no use is made of it at the moment.

**Mr. R. A. Fitch:** All the devices discussed so far appear to have certain intrinsic difficulties, such as the high safety factor required to survive gales, the problem of carrying heavy machinery on a tower, and the low speed of the rotor. These difficulties would, I imagine, become extreme if one desired to go to the larger machines typical of more conventional power stations.

Now there is plenty of energy available, but the problem is to collect it; a similar situation arises with water power, and there the solution is to build a huge concrete dam. In this instance it occurs to me that one might build a concrete funnel to collect the wind. It would be designed for non-turbulent flow and would terminate in a small high-speed rotor which, with the rest of the heavy machinery, would be at ground level. The cost of such a funnel might be excessive, but it should be sufficient to have a massively constructed ring at the mouth, and a much lighter funnel behind. The ring would be strong enough to take a full gale, and there would be servo-operated vanes mounted in it to produce a constant wind velocity at the turbine. The heavier vanes would take account of gradual wind variation, and the lighter ones behind, with short time-constants, would deal with gust variations. Such furling, being static, should prove simpler than the dynamic furling of the rotor blades. On the aesthetic properties of this monstrous conception I am not qualified to speak, but it might have exciting acoustic properties and specialize in sending out invigorating music on windless days. Perhaps the author will point out the difficulties of such a scheme.

## NORTH-WESTERN CENTRE, AT MANCHESTER, 5TH APRIL, 1955

**Mr. J. L. Ashworth:** In the Introduction the author gives a number of reasons for the renewed interest in wind-power generators. So far as public electricity supply in this country is concerned, it is the inability of coal production to match the ever-increasing demands for energy that produces interest in alternative sources of energy.

In view of our serious fuel situation, one would expect that every encouragement would be given to any reasonable proposal for alternative sources of energy. In reality, all sorts of objections are raised when suitable sites for wind-power generators are found. It seems that every site with sufficient wind to merit such an installation turns out to be a beauty spot, with strong supporters determined to prevent the desecration of the countryside. The cost of fighting these objections is heavy, considering the amount of power to be obtained. Unless there is some change in public opinion, supporters of wind generators for public electricity supply are fighting an uphill battle. In this connection, I should like to draw attention to the very reasonable statement at the end of Section 2.1.

In considering the value of wind-power generators for the

›ublic electricity supply system there are two aspects of some mportance, namely the power available on demand, and the otal energy available over a period of time. The former is mportant, since it affects capital investment in plant to meet the naximum demand.

The author also states, in Section 2.2, that in Great Britain he wind must be accepted as truly random. In consequence, vind generators will have little value as a power available on emand. It can, however, make a contribution, even if small, o augment our coal resources. I feel that the greatest applica-ion of wind-power generation will be in undeveloped areas broad, and possibly in isolated premises or communities in this ountry.

I should like to ask whether the author has any figures omparing the losses between geared generators with the losses hat one might get in the double conversion of the Andreau ystem.

**Mr. T. Mensforth:** Turning to the strong opposition on amenity rounds to the erection of windmills in England and Wales, I vould mention that I have not had this difficulty in Scotland, articularly on the Islands, where I have received every encourage-nent. In co-operation with the North of Scotland Hydro-lectric Board, most careful attention is being devoted to securing pleasing appearance for the machines.

As to the troubles at Orkney, whilst progress has been dis-ppointingly slow, this must be expected in pioneering, and the rkney machine was primarily experimental.

Orkney has serious disadvantages as a site for a first large nachine, and many of the setbacks and delays were due to veather and other uncontrollable conditions. The problem of electing a temporary or more suitable permanent testing site ad not yet been solved.

Much has been learned from Orkney, and 250 kW machines nd larger could now be designed with reasonable confidence.

I advocate the cautious approach of first perfecting machines f, say, 250–600 kW, before attempting the very largest, which conomically, I think, may be of about 1 500 kW rating.

**Mr. S. Chaplin:** I should like to confirm, in respect to the 00 kW Enfield plant, the important point made by the author bout the difference between prototype and production design. is most unlikely that the British Electricity Authority would ave commissioned this machine except as the forerunner of omething considerably larger. It was, in fact, regarded by the esigners as suitable for scaling up to 1 000 kW and much of its ost was due to this intention. A 100 kW "depression" type lant for series production would be much simpler, and a design udy of just such a machine is well advanced (Fig. D).

I know a good deal about the potential market for small- and edium-scale plants. The potential demand is enormous but omes for the most part from "poor" areas which cannot afford support research and development single-handed. The ritish Commonwealth appears to lack the machinery needed to o-ordinate demand and to provide the much needed official ncouragement to manufacturers. Much of the splendid work f the Electrical Research Association may be wasted unless this roblem is tackled at an early date.

**Mr. E. W. Connon:** In recent times the emphasis has always een on larger and larger concentrations of generating plant in rder to obtain the maximum economy with thermal plant, and as result the energy available in small pieces from wind and water ave tended to be overlooked. Our ancestors had little or no ther forms of mechanical power, and perforce used wind and ater in proportion to a much greater extent than we do. When ne considers that almost all marine transport was wind-owered, we can see the extent to which the subject has been eglected in recent years. The resurgence of interest to-day is,

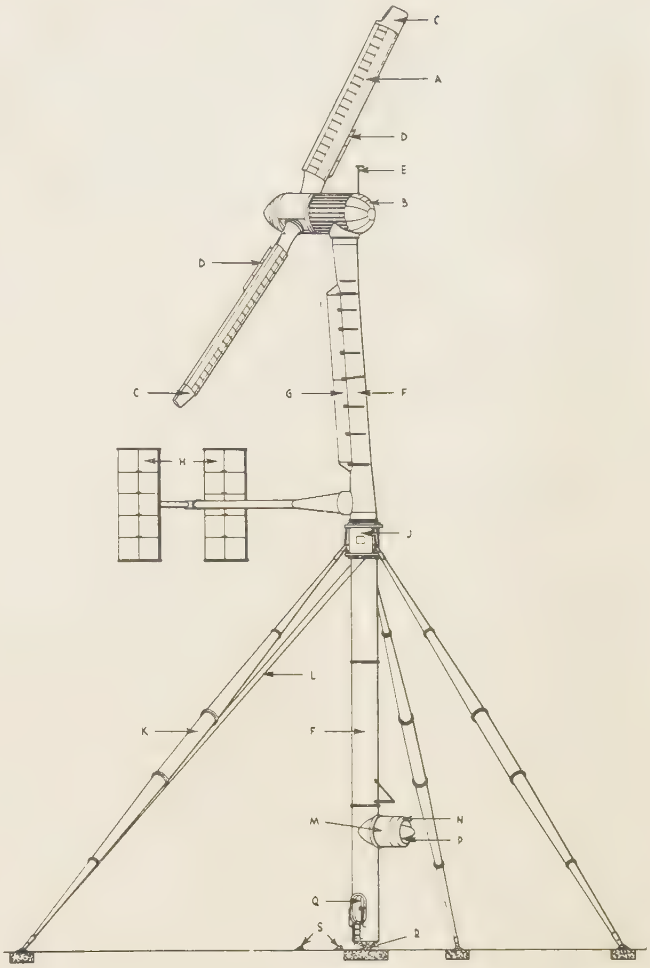


**Fig. D.**—Enfield Mark II 100 kW machine.

Output (full rated) with 30 m.p.h. wind = 100 kW.
Diameter of swept circle = 80 ft.
Height: ground to rotor axis = 129 ft.
Total weight = 33 tons.
Rotor weight = 3·6 tons.
Diameter of lower (circular) section of tower = 4 ft 7 in.
Pitch circle diameter of supports = 124 ft.
Maximum load in each supporting leg ± 15 tons.

A = Rotor: aluminium alloy.
B = Tower head: aluminium alloy.
C = Air outlet ports.
D = Anti-stalling slats.
E = Anemometer head.
F = Tower and air-duct (combined): steel.
G = Fairing.
H = Yaw vanes: aluminium alloy.
J = Upper pintle bearing.
K = Support legs and lifting gear: tubular steel.
L = Anti-torque cables.
M = Alternator.
N = Air turbine.
P = Air intake.
Q = Entrance to control room.
R = Lower pintle bearing, vertical load support and slip-rings.
S = Lifting gear attachments: Permanent.

by contrast, all the more noticeable, and widespread rural distribution systems now enable small quantities of electricity to be collected into the system wherever they are available.

The author divides windmills into three size categories, the two smallest sizes (up to 100 kW) being generally considered for isolated use. In this application the whole matter is bedevilled by the old problem of our inability to store electricity economically, and an important aspect of wind-power utilization seems to be the solution of the storage problem and the development of intermittent loads. The solution of the electrical storage

problem does not seem to have progressed much during the present century.

With regard to the use of larger windmills, the author suggests that they are intended purely as fuel savers. They might also be used to increase to some extent the reliability of supply to thinly populated districts for which only single-circuit distribution lines are economic; for there is a fairly large probability that when a line failure takes place there would be enough wind to maintain supply. Could the author say whether this aspect has been investigated on a statistical basis?

**Mr. A. H. Gray:** Whilst the electrical energy which can be produced from wind is not likely to assume the astronomical figures associated with water power, it appears from the paper that it is worth while to obtain as much energy as possible from wind power. I understand that the wind gains in velocity and constancy the higher one proceeds. Is this of any practical significance or are the heights involved too great for practical purposes?

The Andreau principle described in the paper is very interesting, but I should imagine the advantages which arise from installing the electrical gear at the foot of the tower are outweighed by the economic question. Can the author give us any relative figures showing the cost of installation per kilowatt-hour output using the Andreau and conventional methods?

Referring to Section 4.1, the rapid changes of wind velocity cited must have imposed great difficulties on the governing problems. Can the author indicate any performance figures achieved in practice: in other words, how does the output of the generator change under varying wind conditions?

It appears that practically all the methods described employ a variable-pitch propeller for control purposes. It is appreciated that such an arrangement must cause some mechanical difficulties and I should like to know whether any method employing non-variable-pitch propellers have been used, the control being imposed by some form of variable deflector fitted in front of the propeller and arranged to yaw with it.

Reverting to the electrical aspect, I am interested in the choice of generator. With few exceptions the induction or asynchronous generator appears to be most favoured. It is agreed that such a machine obviates d.c. excitation and complicated synchronizing and voltage-regulating plant, but as always this simplicity is achieved only at a cost. The asynchronous generator demands lagging power-factor load from the supply for its requisite excitation. Hence the machine can only run in conjunction with the supply (this must be a serious disadvantage in undeveloped areas), and furthermore the excitation energy which is required is a considerable proportion of the generator outpu when compared against the conventional d.c. excitation of synchronous generator. The author is, of course, fully aware this and will in all probability have fixed a capacity above whi it seems desirable to use the conventional synchronous generato Could he indicate this capacity?

In general, the control scheme consists of a tachometer whi measures the wind velocity, and when a prescribed velocity h been sustained for a preselected time the windmill is run up near synchronous speed and connected to the system. T governor gear will then take over and endeavour to extract t maximum power output from the generator consistent with t wind velocity. If the wind exceeds a further preselected spe the generator will be disconnected from the system and t windmill furled. Yawing and the like is, I understand, to carried out both by a simple electrical servo device and the c fan-tail mechanical arrangement. The latter arrangement w of necessity be much slower than the servo device and I shou like to know whether any trouble has been experienced owing slow yawing. Originally, I believe all windmills were lock when the generator was not connected to the load; more recen the practice is to allow the propeller to rotate freely and simp adjust its pitch. Is this change introduced owing to the increas capacities of these propellers?

With regard to the protective scheme, this again is simplic itself, since it consists of a standard thermal overload protecti together with fuses or equivalent circuit-breakers. There however, one point upon which I should like further enlighte ment. The location of this equipment must of necessity exposed to the elements and is therefore subject to lightning di charges. The original equipments supplied for this purpo carried comparatively complicated surge-suppression devic Does the author know of any difficulties which have been expe enced owing to lightning discharge, and is he in a position advise whether the present surge-suppression arrangements cou be simplified?

**Mr. A. I. Jones:** It is well known that there are certain types storm in which a high wind velocity is experienced from t direction of the approach of the storm, and as the storm cen passes over the wind yaws through 180° with extreme suddenne On the old-fashioned windmills this produced tail winding a very often resulted in the uncapping of the mill or the displa ment of the wind shaft and sails. I should like to know wheth this possibility is catered for in the prototype designs of t wind-generators, since with the direct-drive machine it mig result in a reversal of rotation of the alternator rotor.

## THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

**Mr. E. W. Golding** (*in reply*): The paper was presented with the objects of describing the investigations on wind-power possibilities which have been made in this country during the last eight years and of reporting the progress made. Mr. Haldane, under whose chairmanship the work of the Wind Power Committee has proceeded, emphasized the continuing need for saving coal in electricity generation, and expressed his disappointment that the progress in plant construction has been so slow. One cannot but agree with him wholeheartedly, especially in view of the fact that the existence of many very favourable sites has been proved by the wind surveys.

Coming from one who has had first-hand experience of the difficulties involved in building and testing a pilot wind-power plant on one of the best—and therefore most exposed—of these sites, Mr. Mensforth's contribution to the discussion is greatly appreciated. We who have worked in close contact with him in Orkney know how arduous this work has been and we c sympathize with him and his colleagues.

It was very gratifying to have the agreement of Mr. Halda and of Mr. Chaplin, who has been concerned with the buildi of the second pilot plant, on the great scope which exists f medium-size wind-driven machines in many parts of the wo as well as in some of the more remote parts of the British Isl Mr. Juul and Dr. Hütter have done valuable work on the develo ment of machines in this category and have brought them to t stage of practical operation. Mr. Juul's statement on th economy is most encouraging, and it is interesting to note t both of these speakers mention the satisfactory operation o number of relatively small machines in parallel. In fairne however, it should be made clear that our two 100 kW machi were not meant to be produced in quantity as medium-sc plants but were, rather, scaled-down models of much lar

ıachines which were expected to have capacities in the range –3 MW. Constructional problems are inevitably different in ıese two ranges of size, and some of the difficulties encountered ave undoubtedly been due to the introduction of somewhat omplicated design features which were thought, rightly or rongly, to be necessary for the larger plant. Step-by-step dvances in size appear to be wise, and the pilot plants were riginally intended by the E.R.A. research committee to provide perating experience and design data before larger construction as attempted. In this they have been, at least, already partly ıccessful in spite of the fact that they have not yet passed from ıe testing stage to continuous operation.

The present E.R.A. research has for its aim simplification and ıeapening of the construction, particularly through the deter- ination of the probable effects of omitting complicating atures.

It may well be, as Prof. Dresden has pointed out, that wind- ower machines need not always be designed to withstand the ghest gust speeds which may very occasionally occur. This is pecially true for some of the less windy areas of the world, ıt in the early stages of development it is natural that perhaps ıdue caution should be exercised to avoid the destruction of pensive experimental plant. Prof. Dresden's description of the ethods of analysis used in Holland is interesting, and there is doubt that the prevailing wind often produces a major share the annual energy.

Both Mr. Atkins and Mr. Ashworth have mentioned the position encountered to the installation of a wind-driven achine in Caernarvonshire, but by no means all of the local sidents objected to the project. Mr. Mensforth mentioned the rdial co-operation which he has received in Scotland; and ıce in Denmark, where such machines are common, they have en accepted without question, it may be hoped that this factor ll not prove a lasting difficulty. Danish experience suggests at Mr. Atkins's fears about high maintenance costs are ıfounded.

Dr. Frith's interesting information on wind variations empha- es the importance of this feature of wind behaviour which we ntinually bear in mind in wind-power work. Mr. Argand's scription of the wind-power investigations in France largely nfirms the agreement between us on the methods to be adopted such work. The wide variations in wind speed which he has easured over an extensive area are borne out by our own experience. Possible difficulties due to rapidly varying power output, mentioned by Mr. Argand, do not appear, however, to have arisen with Mr. Juul's 45 kW plant in Denmark. There is little doubt that Mr. Munro is right in his opinion that a 100–400 kW wind-driven generator operating satisfactorily would make a very valuable contribution for further progress in this subject. He may be correct also in his assessment of the value of energy from the wind as higher than the bare fuel component of thermal generation, but this has been used as a conservative estimate. I am grateful to Mr. Cameron Brown for his remarks—with which I entirely agree—on the potentialities of wind-driven generators to supply farm loads, and for his note on the early work on this subject in which he took an important part.

The scheme suggested by Mr. Fitch is one which has already been suggested, with various modifications, by several people both here and abroad. It has attractions and is being studied, but the constructional costs for the civil-engineering work may prove heavy. Mr. Connon and other speakers mentioned the pressing need for an economical means of storing energy; there is no doubt that this would be a great help in the use of wind power by small communities.

Mr. Gray has raised interesting questions the answers to some of which can be given briefly as follows. Wind speed above a hill summit increases with altitude less rapidly than over level ground; very high towers would be uneconomic. Machines of the Andreau type have not yet been tested sufficiently to indicate their relative economy, but the principle has advantages in convenience of operation and in damping out gusts. The tendency is for the effects of rapid changes in wind speed to be smoothed out by the inertia of large rotors. Fixed-pitch blades have been used satisfactorily in Denmark for machines up to 70 kW capacity. No limits have yet been fixed for the size of induction generators in wind-power plant. So far no difficulty appears to have been encountered from lightning with the wind-driven machines which have been installed. Mr. Jones raised the question of rapid reversal of wind direction; this is catered for by using a sensitive yawing device.

In conclusion, I should like to mention the excellent spirit of co-operation which has been evident, during the past few years, between those interested in wind power in different countries. The free exchange of information and the cordial assistance given in other ways has been a great encouragement and is a good augury for the future.

621.316.5.064.2

Abstract No. 19[illegible]
Dec. 19[illegible]

# INTERRUPTION OF A.C. CIRCUITS

By SING-YUI KING, B.Sc.(Eng.), Ph.D., Associate Member.

(ABSTRACT *of a paper read before the* HONG KONG JOINT OVERSEAS GROUP OF THE INSTITUTIONS OF CIVIL, MECHANICAL AND ELECTRICA[illegible] ENGINEERS *at* HONG KONG, *2nd December*, 1954.)

The paper reviews briefly the mechanism of arc extinction in high-voltage a.c. circuit-breakers. A new method of calculating the inherent restriking transient is described, based on the principle that all electrical transients are caused by residual energy (either electric or electromagnetic or both) left in the circuit when it undergoes a change from one steady state to another owing to the interruption of the circuit. The dissipation of this residual energy gives rise to the restriking transients. Both capacitive and inductive elements can store residual energy by virtue of their charges and currents, respectively. These residual charges or currents can be determined from the steady-state charges or currents before and after circuit interruption. The restriking transient across the circuit-breaker is the sum of the steady-state voltage across the circuit-breaker after circuit interruption and the transient voltage as a result of the residual charges and currents. The method, unlike that of Heaviside's operational calculus, allows the variation of the effective inductance of alternators or transformers with frequency to be taken into account. In polyphase networks, the solutions may be simplified by the symmetrical or related components.

A simple power network, as shown in Fig. 1(*a*), is given as an illustration. A 3-phase-to-earth fault at F will trip the circuit-breaker. To find the restriking transient for the first phase to clear it is necessary to reduce the network to equivalent circuits. Fig. 1(*b*) shows the equivalent circuit (positive sequence) before the opening of the circuit-breaker, and Fig. 1(*c*) shows the equivalent circuit after the clearing of the first phase. For transient oscillations, the voltage source is short-circuited, and the impedances corresponding to their respective appropriate natural frequency for each transient oscillation are multiplied by three in order to reduce the sequence voltage to the actual transient voltage across the circuit-breaker after arc extinction. Fig. 1(*d*) gives the equivalent circuit for transient oscillation.

The restriking transient $V_r$ for the first phase to clear in a 3-phase-to-earth fault is

$$V_r = \sqrt{(2)}V_0\frac{3L_2}{L_1 + 3L_2} + \sqrt{(2)}V_{2a}\cos\omega_a't + \sqrt{(2)}V_{2b}\cos\omega_b''t \quad . \quad . \quad . \quad . \quad (1)$$

where

$$V_{2a} = \frac{3V_0L_2}{L_1+3L_2}\left\{\frac{\dfrac{L_1''}{L_1''+L_2''-\omega_b''^2L_1''L_2''C_1} - \dfrac{L_1}{L_1+L_2}}{\dfrac{L_1'}{L_1'+L_2'-\omega_a'^2L_1'L_2'C_1} - \dfrac{L_1''}{L_1''+L_2''-\omega_b''^2L_1''L_2''C_1}}\right\}$$

$$V_{2b} = \frac{3V_0L_2}{L_1+3L_2}\left\{\frac{\dfrac{L_1'}{L_1'+L_2'-\omega_a'^2L_1'L_2'C_1} - \dfrac{L_1}{L_1+L_2}}{\dfrac{L_1''}{L_1''+L_2''-\omega_b''^2L_1''L_2''C_1} - \dfrac{L_1'}{L_1'+L_2'-\omega_a'^2L_1'L_2'C_1}}\right\}$$

$$f_a'\left(=\frac{\omega_a'}{2\pi}\right),\ f_b''\left(=\frac{\omega_b''}{2\pi}\right) = \text{Natural frequencies.}$$

$\omega_a$ and $\omega_b''$ satisfy the following equations.

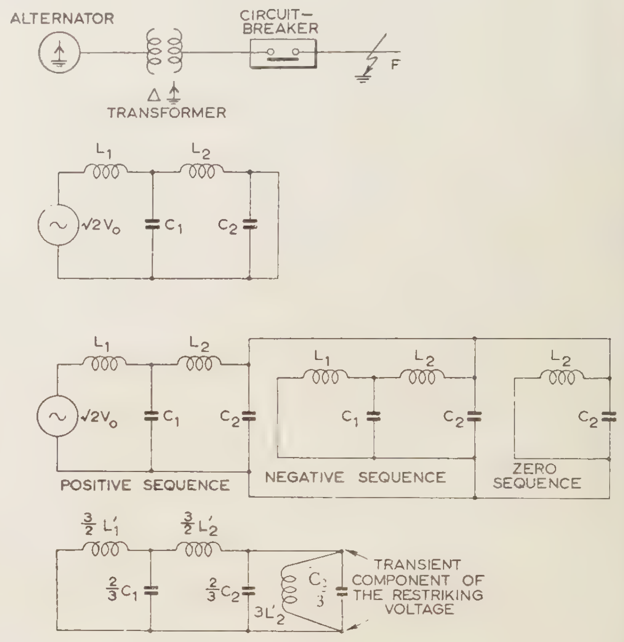


**Fig. 1.**—Simple power network.

In (*b*) and (*c*), $L_1$ and $L_2$ are the 50 c/s inductances per phase of the alternator a[illegible] transformer, respectively, referred to the secondary winding.
In (*d*) $L_1$ and $L_2$ should correspond to the natural frequency concerned.

$$3L_1'L_2'^2C_1C_2\omega_a'^4 - (3L_1'L_2'C_1 + 3L_1'L_2'C_2 + 3L_2'^2C_2)\omega_a'^2 + L_1' + 3L_2' =$$

$$3L_1''L_2''^2C_1C_2\omega_b''^4 - (3L_1''L_2''C_1 + 3L_1''L_2''C_2 + 3L_2''^2C_2)\omega_b''^2 + L_1'' + 3L_2'' =$$

$L_1, L_2$ = Inductances of alternator and transformer respective[illegible] at 50 c/s.
$L_1', L_2'$ = Inductances at frequency $f_a'$.
$L_1'', L_2''$ = Inductances at frequency $f_b''$.

When $L_1 = L_1' = L_1''$ and $L_2 = L_2' = L_2''$, eqn. (1) will be reduc[illegible] to the same form as that given by the Heaviside operation[illegible] calculus. From eqn. (1) it can be seen that the amplitudes $V$[illegible] and $V_{2b}$ depend on $L_1$ and $L_2$ at all three frequencies, i.e. 50 c[illegible] $f_a'$ and $f_b''$.

After a general survey of the different types of circuit-break[illegible] now in use, a discussion of the future trend of circuit-break[illegible] design is also given. It seems that not much drastic improveme[illegible] can be envisaged in design if we use the present convention[illegible] types. For further progress, the new arc-quenching medium [illegible] device should be given due consideration. It is possible that [illegible] using a sand blast, dielectric recovery can be accelerated in t[illegible] residual arc path, since find sand particles can form the nuc[illegible] for the recombination of electrons and positive ions, and al[illegible] induce more effective cooling of the arc space. Superimpos[illegible] high-frequency external electric fields may increase the turbulen[illegible] in the arc space and hence accelerate the dielectric recove[illegible] following a current zero.

Mr. King is at the University of Hong Kong.

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Paper No. 1707 S
Aug. 1954

# PROVING THE PERFORMANCE OF CIRCUIT-BREAKERS, WITH PARTICULAR REFERENCE TO THOSE OF LARGE BREAKING CAPACITY

By J. CHRISTIE, M.I.Mech.E., Member, H. LEYBURN, B.Sc.(Eng.), Member, and J. F. BIRD, M.C., B.Sc., Associate Member.

(The paper was first received 8th February, and in revised form 10th May, 1954. It was published in August, 1954, and was read before the SUPPLY SECTION 23rd March, the NORTH-EASTERN CENTRE 10th January, the WESTERN CENTRE 7th March, and the NORTH-WESTERN SUPPLY GROUP 29th March, 1955.)

## SUMMARY

For more than 20 years the technique of short-circuit testing has been advanced steadily. To-day it has reached a high state of development, and it is opportune to examine the position.

In the paper the characteristics of the main types of circuit-breaker are briefly summarized, and the various aspects of test-circuit severity are considered, both in relation to actual service conditions and to their effects upon the different types of circuit-breaker.

Existing test procedures and methods are reviewed, and suggestions are made for the improvement of some of them and for their being brought more into line with present service requirements. Proposals are also made for methods of approach to certain tests which it has not yet been possible to standardize. Particular attention is paid throughout to the problems associated with the testing of large circuit-breakers.

Finally a brief reference is made to the part played by field tests and the requirements of a modern testing station.

## (1) INTRODUCTION

Circuit-breakers perform a key function in supply systems and must operate with absolute reliability and safety in widely diverse service conditions. It is therefore essential that everything reasonable should be done to ensure that their performance is properly proved. The duties which service conditions may impose on a circuit-breaker are extremely varied, and testing must be sufficiently comprehensive to cover the complete range in order to ensure that performance in one sphere of duty is not obtained at the expense of another.

The main objects of the paper are as follows:

(*a*) To make a critical review of present-day testing methods evolved during the last 20 years and to show how far they correspond with actual service requirements.

(*b*) To suggest modifications to existing test procedure.[1,2,6]

(*c*) To examine the basis of tests which have not yet been included in specifications, and to suggest lines of approach suitable for such tests.

Particular attention is paid to the proving of large high-voltage circuit-breakers, because it is in this region that most of the technical problems arise, and the cost of testing stations large enough for full-scale proving of such circuit-breakers is prohibitive.

The Association of Short-Circuit Testing Authorities has, since its formation, worked continuously to improve the technique of testing[3,4,5] and a number of the points raised in this paper are receiving active consideration by that body. Although the authors are in varying degrees associated with this work, the views expressed in this paper are their own views and do not necessarily represent the views of the A.S.T.A.

In presenting their views the authors aim to stimulate public discussion, in the hope that this will be useful to all those concerned in arriving at the best possible standard test procedure.

The authors are with A. Reyrolle and Co., Ltd.

## (2) BEHAVIOUR OF CIRCUIT-BREAKERS

A short summary of the behaviour of the three main types of circuit-breaker will assist in assessing the value of the tests to which they are subjected and in adopting a testing procedure to suit the characteristics of the circuit-breaker under test.

### (2.1) Oil Circuit-breakers

The outstanding feature of oil circuit-breakers when breaking a short-circuit is that they generate their own arc-extinguishing gases, and these increase in quantity as the arc is lengthened. The pressures produced at large currents are high, and the most common kind of failure here is mechanical. Other types of failure may be concerned with gas disposal, resulting possibly in internal flashovers or, where unbalanced pressures are set up, maloperation of the mechanism.

At lower currents, including limited short-circuit currents, load currents, transformer magnetizing currents and line-charging currents, the problems that may arise are associated with the control of long arcs, the minimization of oil carbonization, the limitation of over-voltages, and in the case of capacitive currents, the withstanding of high shock pressures in arc-control pots.

### (2.2) Air-blast Circuit-breakers

In air-blast circuit-breakers the pressure of the compressed air is fixed and is substantially independent of the arc intensity. The arc-extinguishing property of the circuit-breaker does not therefore increase with the magnitude or duration of the current. Failures with large short-circuit currents may be due to the inability of the flow of air to deionize the arc path fast enough. The number of loops of arcing which may be permitted depends on whether the design is such that the air pressure continues to rise at the end of the first loop. If it does the circuit-breaker may still clear at a subsequent current zero.

At lower currents testing is mainly concerned with finding whether any objectionable over-voltages are produced.

With air-blast circuit-breakers the effects of rate of rise of restriking voltage (r.r.r.v.) are of fundamental importance. (This does not apply to the same extent with oil circuit-breakers.)

### (2.3) Air-break Circuit-breakers

The process of arc extinction in air-break circuit-breakers is fundamentally different from both oil and air-blast. The air-break circuit-breaker depends on the lengthening and cooling of the arc until it becomes unstable. Testing is largely concerned with checking that the arc can be extinguished without producing any tendency to flash over. It is for this reason that such circuit-breakers are usually tested in an insulated framework earthed through a fine-wire fuse. Indication of another kind of failure is given by repeated restriking across the base of the arc chute, and this condition can be determined from the oscillograms of the test.

Other problems, normally encountered at lower currents,

include the correct switching-in of magnetic field coils where these are used and the effectiveness of the means used for forcing small currents into the arc chute.

### (2.4) The Use of Switching Resistors[9, 10, 11]

The performance of oil and air-blast circuit-breakers is sometimes assisted by the use of switching resistors. It is important to appreciate the purpose for which a switching resistor is being used because of the wide variation in its resistance and in its functioning. The following is a brief summary of the ways in which resistors are used and of the values that are assigned to them in e.h.v. circuit-breakers:

(*a*) *For controlling the rate of rise of restriking voltage.*—For this purpose preferably the resistor should at least critically damp the inherent restriking-voltage transient at the full rating and should have a resistance of a few hundred ohms only. The circuit-breaker must be provided with a second auxiliary break to interrupt the current flowing through such a resistor.

(*b*) *For limiting over-voltages due to current chopping.*—For this purpose the resistor should be so proportioned as to increase the circuit power factor to, say, 0·5 when the resistive current is being broken. When this is done any current chopping occurs at a much lower voltage and the tendency to produce over-voltages is reduced accordingly. A resistance of not less than several thousand ohms is normally required.

(*c*) *For preventing voltage build-up due to restriking when interrupting capacitance currents.*—The resistance depends on the capacitance of the system which it must discharge, a reasonable time-constant being about a quarter of a cycle. It is usually of the same order as for (*b*), but the thermal capacity has to be considerably greater.

(*d*) *For voltage grading in multi-break circuit-breakers.*—For this purpose the resistance must be such that the effects of stray capacitance, etc., are swamped. It is usually of the order of 100 000 ohms or more.

The values quoted above apply to linear resistors. Non-linear resistors of appropriate value may also be used in certain instances.

Although occasionally it is possible to combine some of the functions detailed in (*a*) to (*d*), this is not usually the case. In particular, the resistors used for the purposes (*b*) to (*d*) do not, as a rule, modify the r.r.r.v. of the system, which is the object of the relatively low resistance referred to in (*a*).

From the point of view of testing it is important to recognize what type of resistor has been incorporated in the circuit-breaker, so that its limitations may be fully investigated.

## (3) SHORT-CIRCUIT CONDITIONS

It is essential that methods of test should be based as closely as possible upon service conditions. These fall under two main headings: short-circuit conditions, which are discussed in this Section, and normal service conditions. The short-circuit conditions include a wide variety of breaking duties ranging from the rated breaking current down to the limited currents corresponding to remote faults; duties relating to making on to a fault and carrying through fault currents; duties involving breaking under conditions of loss of synchronism, auto-reclosing and others. The way in which these various duties are reflected in the basic circuit characteristics, namely current, voltage, power factor and circuit configuration, which in combination determine the severity of testing, is discussed in this Section.

### (3.1) Current

The effects of symmetrical currents are reasonably straightforward and consistent.

Asymmetrical currents must be considered in relation to the power factor, which controls the degree of asymmetry and the rate of decrement, as illustrated in Fig. 1. It is worth noting

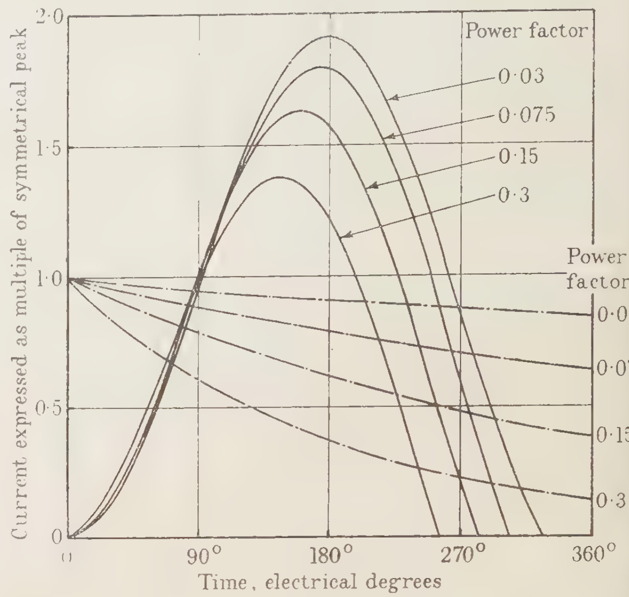



**Fig. 1.**—The effect of power factor on the maximum obtainable current asymmetry and rate of decay of d.c. component.

——— Effect on maximum obtainable asymmetry.
– – – Effect on rate of decay of d.c. component.

that the maximum d.c. component that it is possible to obtain at the first peak with a power factor of 0·15 (the lowest specified for short-circuit test in any standard specification) is 64%, giving a peak current of $1 \cdot 64I$ in the first loop, where $I$ is the peak value of the rated symmetrical short-circuit current. To obtain $1 \cdot 8I$ as required by B.S. 116 for the making-capacity test, the power factor must be reduced to about 0·075. Although this is below the normal values of power factor encountered in systems at full short-circuit currents, the current of $1 \cdot 8I$ thus obtained corresponds reasonably well with the making current in generator circuits during the sub-transient period and thus constitutes adequate proof of the making capacity of the circuit-breaker with the full sub-transient current.

It is unlikely that a circuit-breaker in service will be called upon to break an asymmetrical short-circuit. The exceptions are ultra-high-speed circuit-breakers (including many of those fitted with making-current releases) and those rare occasions when a circuit-breaker opens on a developing fault. In this latter case it is even more rare for the full power to be present. The importance of the asymmetrical test should therefore not be overstressed, and there is a good case for replacing it by some other kind of duty.

For certain circuit-breakers the asymmetrical test will still be required, and it is therefore important that it should be applied in a consistent manner.

The authors consider that the asymmetrical breaking test is inadequately defined in present testing specifications. Arising out of experience, particularly with oil circuit-breakers, it is suggested that, in addition to specifying the current and the degree of asymmetry at contact separation as is done at present, it should also be stipulated that in at least one of the three breaks, constituting the duty cycle, arc-extinction must take place after a major loop and that in no case must the period of arcing be less than the normal period for the particular duty. It also appears necessary that the rate of d.c. decrement should be

specified, and to cater for this, a maximum power factor of 0·075 should be used in asymmetrical tests.

### (3.2) Voltage

The three significant aspects of the voltage relating to short-circuit breaking are the recovery voltage, the arc voltage, and the restriking voltage.

**(3.2.1) Recovery Voltage.***

In power systems, the recovery voltage is usually almost equal to the service voltage. To what extent a reduction is permissible in the test recovery voltage depends upon the characteristics of the circuit-breaker being tested. This is discussed in Section 3.2.2.

**(3.2.2) Arc Voltage.**

The arc voltage and current are a measure of the arc energy. With those circuit-breakers in which the arc voltage tends to be high, the test voltage must not be reduced to such an extent that the arc voltage is limited. This has a bearing on the oil circuit-breaker tests above 500 MVA specified in B.S. 116, where provision is made for a reduction of test voltage on a sliding scale based on the limited outputs of existing testing stations.

Fig. 2 shows that arc length and pressure in an oil circuit-

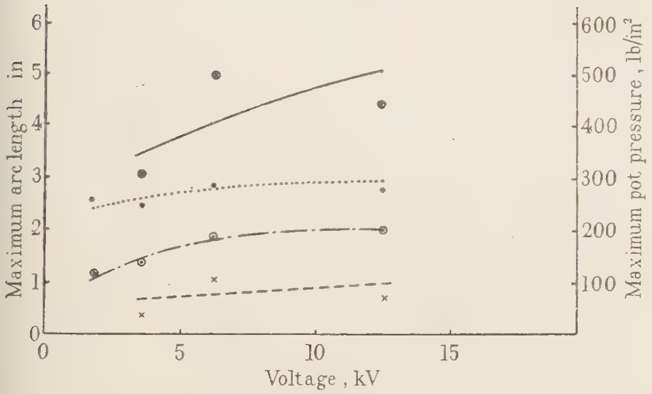



Fig. 2.—Oil circuit-breaker. Experimental curves showing the variation of performance with voltage in terms of arc length and pressure in an arc-control pot.

——— Arc length for 2·5 kA.
—·—·– Arc length for 9·0 kA.
– – – – – Pressure in arc-control pot for 2·5 kA.
········ Pressure in arc-control pot for 9·0 kA.

breaker are not greatly affected by a reduction within limits of test voltage, but tests at reduced voltage do not prove the adequacy of clearances and the insulation security in the presence of arc products. It is therefore concluded that, although some reduction in test voltage is permissible with oil circuit-breakers owing to their relatively low arc-voltage characteristics, such tests cannot be considered to be the equivalent of full-scale tests from every point of view.

With air-blast circuit-breakers experience has shown that no appreciable reduction of test voltage can be permitted, and Fig. 3 shows how the performance of an air-blast circuit-breaker varies with test voltage.

With air-break circuit-breakers a reduction in test voltage is not permissible either, because their ability to clear short-circuit currents is associated fundamentally with high arc voltages.

* It is suggested that the voltage appearing across the first break to clear in a 3-phase circuit-breaker, which, in a system with the neutral earthed and the fault clear of earth, may be as high as $1 \cdot 5V/\sqrt{3}$ (where $V$ is the system voltage), should be known as "the momentary recovery voltage."

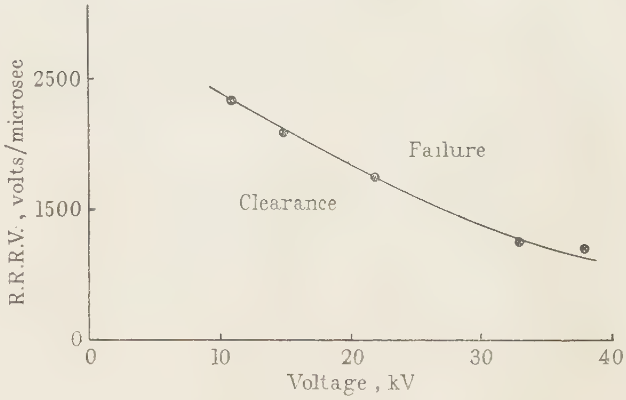



Fig. 3.—Air-blast circuit-breaker. Experimental curve showing the variation of performance with voltage in terms of r.r.r.v. at the point of failure.

**(3.2.3) Restriking Voltage.**[8]

The effect of restriking voltage is most often thought of in terms of r.r.r.v. This, of course, is only one aspect. Other equally important factors are the shape of the transient and its amplitude factor.

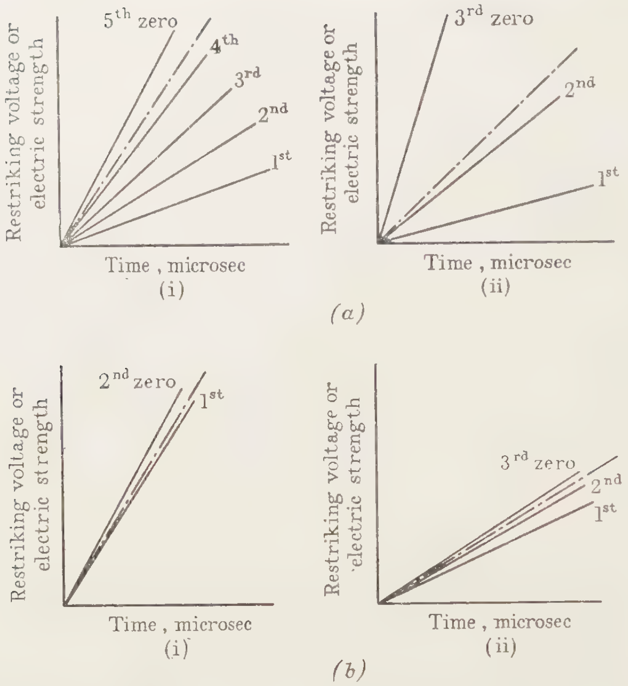
It is becoming the practice to define restriking-voltage severity in terms of r.r.r.v. and amplitude. This is adequate for single-frequency transients.

In service the restriking-voltage transients can be quite complicated. They may be a simple exponential, a single-frequency or a complicated multi-frequency.

Where the testing transient is single frequency (or with only minor higher-frequency components) the only safe method is to have a testing transient which is at all times greater than the service transient. If a circuit-breaker is satisfactory when tested in this way there will be no doubt of its being satisfactory in service.

When the testing transient is multi-frequency, which is sometimes unavoidable, if the same method is followed an undue stress may be imposed upon the circuit-breaker. This would be the case when the initial r.r.r.v. was high for a short period. Methods have therefore been evolved to arrive at an equivalent single-frequency transient (or an equivalent r.r.r.v.), which can be used as a measure of its severity. The most notable of these is that produced by the A.S.T.A.[5] Whilst at the best such a method can only be approximate, experience in working with it appears to have been satisfactory so far.

An assessment of the effects of the restriking-voltage transient on different types of circuit-breaker is useful to the testing engineer. These effects are not the same for air-blast circuit-breakers and oil circuit-breakers, and the difference is illustrated in the much simplified curves of Fig. 4. In this Figure the r.r.r.v. across the circuit-breaker contacts is compared with the rate of rise of electric strength at consecutive current zeros. With air-blast circuit-breakers, in which the arc-extinguishing medium is supplied from an external source, the rate of rise of electric strength can increase only slightly (with build-up of pressure) as the arc continues. A small change in r.r.r.v. can therefore be critical as between success and failure. In the case of oil circuit-breakers in which the arc-extinguishing effects rise rapidly as the arc is lengthened, the rate of rise of electric strength increases proportionally at each current zero. A small change in r.r.r.v. is then likely to affect the arc duration by only a single loop one way or the other. Whether at large currents a further loop of arcing can be permitted will depend largely on mechanical considerations.




4.—Simplified diagram illustrating the effect of r.r.r.v. on arc duration in oil and air-blast circuit-breakers.

——— Rate of rise of electric strength at consecutive current zeros.
—·—·— Rate of rise of restriking voltage.

(*a*) Oil circuit-breaker.
(i) Small currents.
(ii) Large currents.

(*b*) Air-blast circuit-breaker.
(i) Small currents.
(ii) Large currents.

In the past, the absence of standard values of r.r.r.v. for testing has meant that, in many cases, individual consideration has had to be given to them. In certain instances excessive values of r.r.r.v. have been specified. The need for standardization here, based on realistic system conditions, is very great, and a considerable amount of work has been done in various places to assess the values which may occur. A large number of conditions have been calculated relating to systems of various sizes between 66 and 275 kV (see Section 8). Some of the curves showing the maximum r.r.r.v. which can be obtained on such systems under practical operating conditions are shown in Fig. 5. These curves are applicable mainly to power stations or other locations where the major power in-feed is through transformers. For other locations where the major in-feed is through lines or cables the r.r.r.v. is likely to be much lower.

It will be noted that the r.r.r.v. corresponding to the full short-circuit MVA of the system is almost constant, irrespective of voltage, and that there is similarly comparatively little difference between the highest values of r.r.r.v. obtainable, except at 66 kV.

On the basis of these calculated curves it has been possible to arrive at a set of values of r.r.r.v., corresponding to the different standard test duties, which might reasonably be taken as standard. These are given in Table 1.

It will be noted that the values proposed for the 30% ratings are lower than the maximum values shown in the curves. It should, however, be noted that most of the knee points in this region occur at less than 30%, e.g. 8 800 volts/microsec on the 275-kV curve occurs at 880 MVA, which is about 12%, and from this point of view alone the choice of the lower value of 7 000 volts/microsec is justified.

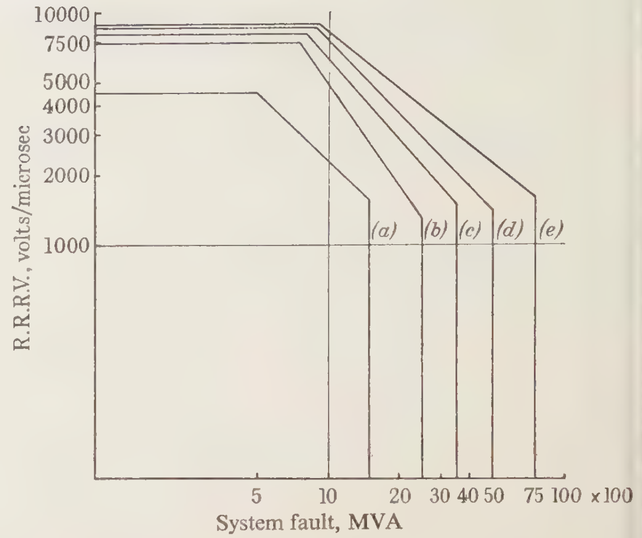



**Fig. 5.**—Envelope curves showing the maximum values of r.r.r.v which are liable to occur under practical conditions with differen values of system fault power.

(*a*) 66-kV systems.
(*b*) 110-kV systems.
(*c*) 132-kV systems.
(*d*) 220-kV systems.
(*e*) 275-kV systems.

**Table 1**

| Service voltage | R.R.R.V. at the given percentages of rated breaking capacity | | |
|---|---|---|---|
| | 30% | 60% | 100% |
| kV | V/μs | V/μs | V/μs |
| 66 | 5 000 | 2 500 | 1 500 |
| 110 | 7 000 | 2 500 | 1 500 |
| 132 | 7 000 | 2 500 | 1 500 |
| 220 | 7 000 | 2 500 | 1 500 |
| 275 | 7 000 | 2 500 | 1 500 |

At testing stations it is usually possible at the higher short circuit MVA to produce restriking-voltage severities in excess o those met with in service. At the lower MVA this is not sc and recourse has sometimes to be had to unit tests in order t increase the r.r.r.v. A typical example of the values which ca be obtained and the relation they have to service conditions i given in Fig. 6. A further reference to this point is made i Section 4.2.[12,14]

A study of published information relating to service condition indicates that the amplitude factor usually lies between 1· and 1·8.

Likewise for testing stations it has been shown[13] that th natural amplitude factors fall in much the same range with tendency towards a minimum of about 1·4 in those circuit which give single-frequency restriking-voltage transients Standardization of the amplitude factor based on system con ditions is desirable.

### (3.3) Power Factor

The effect of the power factor on asymmetry has already bee dealt with (see Section 3.1). It only remains to note that th power factor also decides the instantaneous voltage at curren zero and therefore has a marked effect on the amplitude of th restriking voltage. When the power factor is high the reductio in amplitude of the restriking voltage can be considerable.

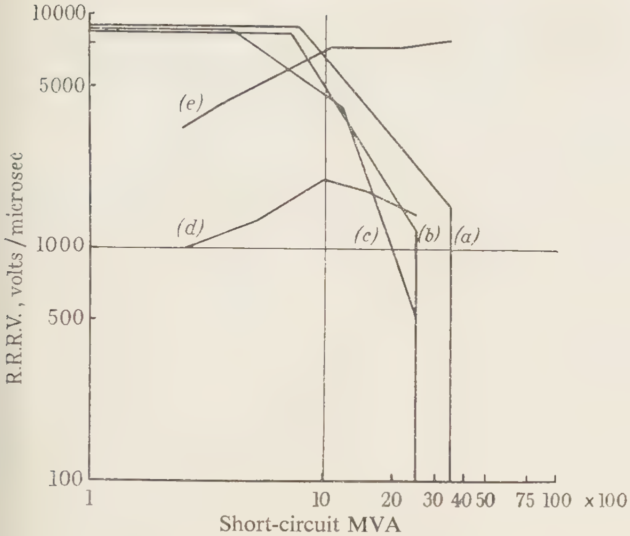



**Fig. 6.**—Envelope curves for 132 kV showing the comparison between values of maximum r.r.r.v. calculated for representative systems and those calculated for the British Grid system, together with values available at testing stations.

(*a*) Calculated characteristic for representative systems with 3 500 MVA maximum fault capacity.
(*b*) Calculated characteristic for representative systems with 2 500 MVA maximum fault capacity.
(*c*) Calculated characteristic for the British Grid system.
(*d*) R.R.R.V. obtainable at all British testing stations[12, 14] not using unit tests.
(*e*) R.R.R.V. obtainable at a typical testing station using unit tests on one unit of a 4-break circuit-breaker rated at 3 500 MVA.

### (3.4) Circuit Configuration

The configuration of the circuit can influence the circuit-breaker under test in a variety of ways as follows:

(*a*) The physical arrangement of the external connections to open-type circuit-breakers can affect the electromagnetic forces which may act upon the arc.
(*b*) In multi-break open-type circuit-breakers the proximity of earthed screens or walls can affect the voltage distribution.
(*c*) The series or parallel connection of the resistance and the reactance critically affects the restriking-voltage transient.
(*d*) The position of the current-limiting impedance and the position of the earth in the test circuit may determine the voltage stressing of the circuit-breaker during the breaking process.
(*e*) Where a circuit-breaker is of non-symmetrical construction (usually the case with single-break circuit-breakers) the way in which it is connected in circuit may influence its performance.

Care must be taken to ensure that the circuit arrangements are in accordance with service conditions.

## (4) METHODS OF TEST UNDER SHORT-CIRCUIT CONDITIONS

There is little difficulty in reproducing all the short-circuit conditions discussed in the previous Section at most modern testing stations for circuit-breakers rated up to, say, 750 MVA. There is usually only one exception, namely the reproduction of the high r.r.r.v. associated with fault values corresponding to 30% or less of the rated breaking capacity. This can usually be overcome by a knowledge of the characteristics of the circuit-breaker under test in this region, and experience in service indicates that such a solution is satisfactory.

With large circuit-breakers, however, namely those rated in excess of 750 MVA, there is an economic problem; the building of testing stations to prove, by means of full-scale tests, circuit-breakers rated at, say, 275 kV 7 500 MVA is prohibitive, and means must therefore be found to prove them by other than full-scale tests, e.g. by single-phase tests, unit tests or synthetic tests.

Although most of the following Subsections are applicable to all circuit-breakers, the emphasis in many of them is upon the testing of large circuit-breakers, and those dealing with single-phase, unit and synthetic tests apply to large e.h.v. circuit-breakers only.

### (4.1) Single-phase Testing

The economic advantage of proving large high-voltage circuit-breakers by single-phase tests is obvious and need not be enlarged upon. Such testing is justified where the poles of a breaker are separate and where the mechanical operation is independent of whether or not fault current flows in all phases. This can be checked by 3-phase full-current tests at low voltage. Two points only need then be considered when relating single-phase tests to the corresponding 3-phase tests.

The first is that in a single-phase test the duration of the final loop of current is determined solely by the degree of asymmetry. In a 3-phase test, however, when the first phase has cleared, a change of phase occurs in the current flowing in the two other phases. This results in a shortening of the current loop in one phase and a lengthening in the other. The main practical importance of this is felt only when it occurs at the same time as a high degree of asymmetry. Compensation can be made in single-phase tests where this is thought to be necessary, but in the authors' experience it can generally be ignored.

The other problem is to determine which test voltage is correct. The value given in the international specification, I.E.C. 56, and in B.S. 116 is $1 \cdot 5 V/\sqrt{3}$, where $V$ is the system voltage. This value (the momentary recovery voltage, see footnote to Section 3.2.1) is based on a 3-phase fault to earth in a non-effectively earthed system or a 3-phase fault clear of earth in any system irrespective of the method of earthing. While in the authors' opinion a good case can be made for a reduction of the factor of $1 \cdot 5$ for any system, this is of little practical importance with systems whose neutral point is earthed through a resistance or reactance or is insulated, i.e. mainly at the lower voltages. At the very high voltages, however, it is quite another matter. Here, effectively-earthed systems are becoming more and more accepted, while the possibility of a 3-phase fault clear of earth on a high-voltage line, equipped with earth wires, is remote. The chance that such a fault might occur with full MVA is so much more remote that it could reasonably be neglected. It is useful, therefore, to study the conditions which may exist on an effectively-earthed system. This has been defined, in effect, as a system in which the maximum r.m.s. voltage to earth which can exist on a sound phase when there is an earth fault on one of the other phases is $0 \cdot 8 V$. It follows from this that the maximum recovery voltage which may appear momentarily across the break of a circuit-breaker is also $0 \cdot 8 V$ or $1 \cdot 38 V/\sqrt{3}$. This may occur on the second phase to clear in the event of a 3-phase fault to earth.

There are, however, other items which must be taken into account in assessing the severity of duty on the circuit-breaker. The most important of these is that the momentary recovery voltage in an interruption involving more than one phase is normally of very short duration, being greater than the peak phase-neutral voltage for a few milliseconds only after arc extinction. The voltage then falls and the steady phase-to-neutral value of the recovery voltage will nearly always be established before the next peak occurs. To maintain a high recovery voltage in single-phase testing is thus unnecessarily severe.

It is impossible to make an accurate assessment of all these effects, but the authors believe that there may well be considerable justification in the case of circuit-breakers intended for use on effectively-earthed systems for making single-phase tests at the

100% duty at $V/\sqrt{3}$, or possibly at a compromise value of $1 \cdot 2V/\sqrt{3}$, leaving the lower test duties to be done as hitherto at $1 \cdot 5V/\sqrt{3}$. The general consensus of opinion in America and a large body of Continental opinion appears to favour a reduction of the factor $1 \cdot 5$.[7,17,18,19]

### (4.2) Unit Testing[15,16]

Even if advantage is taken of single-phase tests, it is still economically impossible to make anything like full-scale tests on some of the largest circuit-breakers.

Although experience with unit tests applied to large multi-break circuit-breakers is still somewhat limited, they are proving very satisfactory, provided that adequate precautions are taken. This involves preliminary testing to determine such matters as:

(*a*) Voltage distribution across the breaks (so that the correct unit test voltage can be assessed).
(*b*) Independence of the circuit-breaker to stray electric fields (which may be brought about by capacitance grading or resistance grading).
(*c*) Independence of the circuit-breaker to post-arc current effects.
(*d*) Uniformity of performance of individual units.
(*e*) Absence of interference between breaks.
(*f*) Effect of contamination of external insulation.

It is understood that rules for the making of unit tests are in course of preparation by the A.S.T.A. and will soon be in force. It is not wished to anticipate these in any way, but it is apparent that much of the validity of unit tests will depend on satisfactory measurement of voltage distribution and the ability to demonstrate that this is unimpaired by the arc and post-arc conductivity effects.

The determination of the static voltage distribution is largely a matter for the laboratory, and several methods are employed. Preliminary determinations by models immersed in electrolytic tanks have been found to give a useful guide for further tests.

Other measurements involve the application of 50-c/s and impulse voltages under a wide variety of conditions in which the configuration of conductors, the proximity effect of earthed screens and the point of application of the earth are taken into account.

From the various tests which must be made as indicated, the unit test voltage will be derived. However accurately this may be done, it is apparent that its validity will be doubtful unless it can be shown that the voltage distribution is substantially unimpaired during the time the circuit-breaker is interrupting the short-circuit current. There are two periods involved, and the distribution of voltage should be measured in both: first there is the arcing period, and the distribution of arc voltage will be a measure of the distribution of duty between the breaks; secondly there is the recovery voltage distribution, and this is an indication of the distribution of severity.

The measurements are best made with full current and the highest obtainable voltage and simultaneously on as many breaks as is possible. Complications are introduced since the voltage dividers and leads to the cathode-ray oscillograph may affect the voltage distribution, and care must be taken to ensure that if they do so due allowance is made.

It should be noted that when making unit tests the r.r.r.v. is reduced in proportion to the unit test voltage. This is of great help when tests are being made at outputs where the test-plant r.r.r.v. is lower than in service. This applies particularly at the lower outputs (see Section 3.2.3).

On the subject of unit testing, mention may be made of the method of connection in which a 3-phase supply is applied to the single pole of a multi-break circuit-breaker, one of the phases, for example, being connected to the common point and the two others to the outer points.[28] Since there is a phase displacement between the currents in the adjacent breaks, it is matter for speculation how far this method is valid when applie to breaks contained in a common enclosure unless they can b proved to function independently of each other. Howeve where the breaks are independent the method is comparabl with unit testing.

Unit tests are now being widely used, and the technique c making them is being improved. In the authors' opinion, un testing, together with single-phase testing, will provide th main basis for proving large circuit-breakers for some years t come.

### (4.3) Synthetic Testing[26]

The number of synthetic testing schemes which have bee proposed is large, but there are only three main types. In th first, the current and recovery voltage are provided from differer sources. In the opinion of the authors the best method in th group is illustrated in Fig. 7.[23,24] Here the current is provide

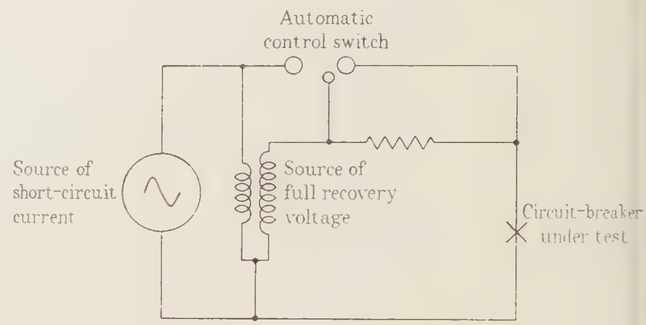



**Fig. 7.**—Circuit for two-source type of synthetic test.

by a lower-voltage source, and the full recovery voltage is auto matically applied at every current zero by a switching devic The main objections to this scheme appear to lie in a tendenc to prolong the current-zero pause, and a possible limitation c the arc voltage.

The second group consists of a device for charging a condense from a low-power source and then discharging it, usually with 50-c/s oscillation,[25] through the circuit-breaker under test. Th authors have not had the opportunity of studying this metho at first hand, but it would seem to offer very little saving i capital cost if carried to its logical conclusion.

The third group consists in testing a scale model and extra polating the results.

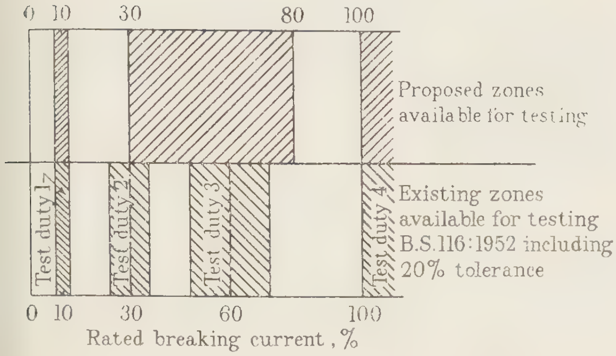
None of the three methods mentioned are, as yet, suitable fc formal proving of circuit-breakers, but valuable informatio may be obtained from any of them in the course of research an development.

### (4.4) Selection of Test Duties

The present specification requires that tests be made at 10%, 30%, 60% and 100% of the rated symmetrical breaking capacit within limits of $\pm 20\%$ of these values, except for 100%. I order to get the best output from a test plant at any particula voltage when testing large circuit-breakers it may be desirabl to have a rather more flexible test schedule; and it is suggeste that the 30% and 60% duties be replaced by two duties to b made at any value between 30% and 80%, provided that th difference between them is not less than 25% and not more tha 50% of the rating. Fig. 8 illustrates the effect of this.

### (4.5) Making Tests

The problem of making on to short-circuit currents is prin cipally mechanical, and such tests are in the main a check o




ig. 8.—Diagram showing the effect of the proposed change in test duties 2 and 3.

ıe strength of the contacts, the mechanism and the general tructure. For the making duty, circuit-breakers are divided ıto two broad categories: those that close fully home and latch, nd those that do not. It is required that those that do not ıtch shall be trip-free.

The main application for non-latching circuit-breakers is at ıe lower voltages where heavy short-circuit currents may make ıtching uneconomical. In this case, the provision of an auto-ıatic instantaneous tripping feature (mechanical or electrical) s part of the circuit-breaker is the usual practice. It is essential ı testing to prove that such a feature operates correctly under ıort-circuit conditions.

Circuit-breakers which are intended to close and latch must e shown to be capable of doing so. It is fairly common practice ) make such circuit-breakers trip-free to some extent; for xample, during the latter part of the stroke. The operation of ıis feature can best be proved in a make-break duty.

On the electrical side the extent and effects of the arcing before ıe contacts touch must be checked. This can be done com-letely only if tests are made with full voltage and current. If ıade single-phase, the test voltage should be $V/\sqrt{3}$. If tests re made with reduced voltage, it may be desirable to simulate ıe effect of the full-voltage arcing by means of a piece of fine ıse wire of appropriate length attached to the fixed contacts. his presents no difficulty where the making contacts are external, ut it is difficult when they are internal and perhaps immersed ı oil. In that event the synthetic test circuit of the two-source ype mentioned in Section 4.3 and illustrated in Fig. 7 may be sed. It would appear to have no such limitations for making sts as it has for breaking tests.

### (4.6) Short-time Current-carrying Tests

The mechanical effects associated with short-time currents e to some extent covered by the making-current tests. But oubles such as contact chatter and thermal effects, or a com-ination of mechanical and thermal effects, can occur during ıe period of short-time current flow (1–3 sec), which might not e noticeable in a making-current test.

Test voltage plays virtually no part in these tests, and it is ıerefore permissible to make them at the lowest convenient oltage. In this way it is possible to keep the current decrement s low as possible, and this enhances the value of the tests.

### (4.7) Make-Break Duties

In certain circumstances the stresses imposed by a make-reak duty can be more severe than either a make or a break ken separately. This applies when the arcing before the ntacts touch is appreciable, because the gases so liberated fect the performance on the subsequent break.

B.S. 116, while specifying for test duty (iv) B–3–MB–3–MB, permits this to be split into M–3–M and B–3–B–3–B, if such a procedure is more convenient to the testing station. This concession is invaluable where large circuit-breakers are being tested, but it is the authors' opinion that where the make duty is made in this way, a supplementary test duty MB–3–MB should also be performed. Here it should be the aim to make the current comply as closely as possible with the specified values for the making and breaking duties. Where this is not possible, the circuit should be set for the required making current, and if the breaking current is slightly low the test should be acceptable.

Where a make-break duty is made single-phase the correct test voltage for the make operation is $V/\sqrt{3}$, but the test voltage for the break operation specified in I.E.C. 56 and B.S. 116 is $1 \cdot 5V/\sqrt{3}$. To comply with the specifications it would be necessary to do the whole make-break duty at the higher voltage. However, if the proposal in Section 4.1 were accepted, i.e. to adopt a factor of $1 \cdot 0$ or $1 \cdot 2$ for single-phase tests at 100% duty in e.h.v. circuit-breakers, this difficulty would be overcome.

### (4.8) Auto-reclosing Duties

Auto-reclosing duties may be high-speed or low-speed or a combination of both. High-speed auto-reclosing is usually associated with large high-voltage circuit-breakers. This can be represented by B–$t$–MB where $t$ is the dead time of the circuit. In service it must not be less than the time required for the path of the fault arc to be deionized, so that reclosure of the circuit-breaker does not cause it to be re-established. Typical minimum values at voltages over 100 kV are 10–15 cycles. This test duty can usually be reproduced at testing stations, but the current broken in the second break operation will often be low. Some tolerance here should therefore be accepted.

The more complicated auto-reclosing duties are difficult to reproduce in testing stations. It has, however, been stated that where the dead time is greater than 10 sec the time interval is not likely to be critical within fairly wide limits in oil and air-blast circuit-breakers. This opens up the possibility of simulating the more complicated duties by a succession of B–$t$–MB duties made at intervals of, say, 3 min, which is possible at most testing stations.

When a circuit-breaker has been proved by full-scale or unit tests for normal break duties it is necessary to check the auto-reclosing performance only at 100% rating and at the current giving the longest arc. Since the B–$t$–MB auto-reclosing duty is more severe than the supplementary make-break duty described in the previous Section, the make-break duty can be omitted if the auto-reclosing duty is done.

### (4.9) Single-phase and 2-phase Short-circuits

The breaking of single-phase and 2-phase short-circuits introduces other factors which are mainly mechanical; and where all three poles of a circuit-breaker are coupled in such a way that uneven stressing may cause trouble, it is advisable that this point should be checked by test.

Although, in certain system conditions of earthing, the single-phase fault current can exceed the balanced 3-phase fault current, this condition is not common and no special account need normally be taken of this.

### (4.10) Out-of-Synchronism Conditions[15, 18, 19]

Large high-voltage circuit-breakers are often used for controlling tie-lines between power stations or groups of power stations and may therefore have to open when there is loss of synchronism. Under certain conditions of earthing and simultaneous faults it would be possible for very high voltages to

appear across the poles of a circuit-breaker opening a tie-line connecting together power stations which have fallen out of step. For example, the worst possible condition from the point of view of voltage would occur if two systems, each earthed by arc-suppression coils and connected with a single tie, were to fall apart with an earth fault on each. This could produce a recovery voltage of $2V$ (or $3{\cdot}47V/\sqrt{3}$). Similarly, loss of synchronism between one such system faulted, with the other unfaulted, could produce a recovery voltage of $2{\cdot}73V/\sqrt{3}$. Arc-suppression coils are not now normally used at the high voltages at which tie-lines connecting together power stations are energized, and since the fault conditions envisaged are in any case improbable they may reasonably be ignored. A study of power-system conditions over a number of years has convinced the authors that the most severe duty a circuit-breaker would be likely to meet under asynchronous conditions on high-voltage systems, where solid earthing is the most common practice, would be to break 25% of the rated short-circuit current at $2V/\sqrt{3}$ (or possibly $2{\cdot}1V/\sqrt{3}$). A test at these values is therefore all that is required. This seems to be in line with the conclusions of most investigators both on the Continent and in the United States, except that in the United States a test voltage of $2{\cdot}5V/\sqrt{3}$ is occasionally mentioned.

### (4.11) Breaking Limited Short-circuit Currents

The lowest short-circuit test specified at present is 10% of the rating, except where there is reason to believe that a critical current exists below this value. Circumstances can occur in service, for example on a remote fault, where it is necessary to break reactive fault currents between the 10% rating and the highest transformer magnetizing currents, and a circuit-breaker should be able to interrupt such currents. It is therefore often advisable to explore this zone even though there are no special indications of a critical current. An additional test at 5% will usually be adequate.

There is one aspect of tests in this range which is worth considering. In service when a fault current of low magnitude is to be cleared, the bulk of the reactance usually lies between the circuit-breaker and the fault. This has an important effect on the distribution of voltage stresses inside the circuit-breaker during the arcing period.

While this does not often affect the performance of large circuit-breakers, particularly those in which the poles are separated, it can have an effect on the operation of smaller circuit-breakers, especially air-break type. With such circuit-breakers it is therefore advisable to make some tests in this range with the greater part of the current-limiting reactance, say 80%, connected between the circuit-breaker and the fault point. This is sometimes difficult to arrange physically, and as the liability of circuit-breakers to fail under this condition is not great, this point should not be overstressed.

### (4.12) Special Tests on Switching Resistors

Although, in general, the tests required to prove circuit-breakers using switching resistors are the same as for those without, it does not necessarily follow that the switching resistors themselves are adequately proved in the process, particularly where unit tests are used.

It is possible in multi-break circuit-breakers using switching resistors for an arc to be re-established after current zero in only some of the main breaks, the circuit being completed through the resistors associated with the other breaks. This imposes high stresses both from voltage and thermal effects, and it is necessary to check that the switching resistors are capable of withstanding any such condition which may arise.

### (4.13) Effect of Frequency

Although strictly speaking the effect of frequency on short-circuit performance is outside the scope of the paper, the results of tests on an oil circuit-breaker at 25 c/s may be of interest since they give an indication of the relative performance at different frequencies.

Tests have indicated that the short-circuit breaking duty of an oil circuit-breaker may be more severe as the frequency decreases (and vice versa). This is because the longer duration of the current loops may cause an overall lengthening of the arc. If a circuit-breaker is to be installed on a system where the frequency differs appreciably from the standard, this must be taken into account.

## (5) NORMAL SERVICE SWITCHING CONDITIONS AND METHODS OF TEST

Switching conditions in normal service, as distinct from short-circuits, include the switching of load currents, of transformer magnetizing currents and of line-charging currents; of less importance, because much less frequent, is the switching of shunt reactors and capacitor banks.

With the exception of load switching all these conditions have one feature in common, namely their liability to produce over-voltages. The maximum permissible over-voltages can be established only in relation to the insulation levels of power systems. This is a subject on its own on which much work has been done, and agreement among the engineers concerned is in sight. The values for the maximum peak voltages to earth which may be permitted are expected to be of the order of 5 times the normal phase-to-neutral voltage in the 3·3–11 kV range, 4·5 times in the 22–100 kV range and 4 times above 100 kV.[22]

### (5.1) Load Switching

The load-switching duty in circuit-breakers will nearly always be easier than breaking limited short-circuits and need not normally be considered. Possible exceptions are circuit-breakers where the normal load current is high or where the number of operations to be expected in service is abnormally large (e.g. arc-furnace control), although here the main concern will be with the durability of the contacts, and with the degree of oil carbonization, where oil is present.

### (5.2) The Breaking of Transformer Magnetizing Currents[15,2]

The phenomenon of the breaking of transformer magnetizing currents has been very fully dealt with elsewhere, and it is proposed to concentrate here on the practical implication as far as testing is concerned.

The measurement of transformer magnetizing currents presents two problems: the first is that the harmonics are often very marked, and the second is that under transient magnetizing conditions the current may be almost wholly displaced from the zero line. Reliable measurements can therefore be made only of peak currents; steady-state peak currents of 50 amp and transient peak currents of 250 amp may be taken as being representative of maximum service conditions.

The extent to which over-voltages may be produced depends on a great variety of factors. On the one hand there are the installation factors, such as the size and arrangement of the transformer, the degree of damping provided by the core losses, the presence or otherwise of tap-changing reactors, and the capacitance between the connections and earth. On the other hand are the operation factors such as the magnitude of the current to be broken, whether interruption takes place during the transient or the steady-state and the maximum chopping current of the circuit-breaker.

The extent to which testing is possible at testing stations is

sually limited by the difficulty in obtaining ordinary power ·ansformers for testing, because the testing-station transformers ften have different core-damping characteristics, while if the ırrent is limited by the use of air-cored reactors, which are sually a part of the testing-station equipment, misleading esults can be obtained. Some tests have been made to correlate esults obtained on testing-station and ordinary power trans-ormers, and this work is continuing.

Experience indicates that the over-voltages produced in service re moderate; the highest over-voltages occur where tap-changing eactors are used which, because of their air-gaps, increase the agnetizing current taken by the transformer and reduce the amping effects when current chopping takes place. Pending le development of an agreed test circuit in testing stations presentative of ordinary power transformers, it is suggested ıat circuit-breakers which are suspected of producing high ver-voltages when switching magnetizing currents be checked gainst the known characteristics of a similar circuit-breaker hich has been tested with an ordinary power transformer.

### (5.3) The Switching of Shunt Reactors

Although there are certain similarities between the switching shunt reactors and of transformer magnetizing currents, ere are two important differences as follows: first, the range steady-state currents in shunt reactors usually lies between ) and 250 amp r.m.s., whereas the steady-state transformer agnetizing currents are much smaller. This means that, though the maximum current chopped may be limited with ansformer magnetizing currents, no such limit exists in the se of shunt reactors. Secondly, the damping in shunt reactors much less than in power transformers because they are either r-cored or have an air-gap in their magnetic circuit. The effect both these differences is to produce much higher switching ver-voltages. Tests made with air-cored reactors installed at a sting station appear to give fairly representative results.

### (5.4) The Breaking of Line-Charging Currents[15, 19]

The breaking of line-charging currents gives rise to two main oblems, namely the production of over-voltages and the tting up of high shock pressures in arc-control pots of oil rcuit-breakers. At lower voltages these problems are not very oticeable, but they become increasingly important as the system oltage increases, say above 100 kV, and occasionally at 66 kV hen long cables are being switched. The main reason is that e dielectric energy stored in the capacitance of cables or verhead lines increases as the voltage increases.

The mechanism of voltage build-up, when the charging ırrent of lines or banks of capacitors is interrupted, has been escribed at length in several places, and is well known. It is essential part of this process that a succession of restrikes ould occur in the circuit-breaker prior to the arc being finally tinguished. An important distinction has been drawn between hat might be termed minor restrikes, which occur when the c has been extinguished for less than one-quarter of a cycle, ıd which cannot leave an enhanced voltage on the line when the c is extinguished, and major restrikes which occur when the c has been extinguished for more than one-quarter of a cycle, ıd which may leave an enhanced voltage on the line in similar rcumstances. The difference is illustrated in Figs. 9(*a*) and 9(*b*). nless this enhanced voltage is left on the line it is impossible r the process of voltage build-up (with associated high transient eaks) to begin at all. In judging the performance of a circuit-eaker it is useful to take into account the number of major strikes in addition to the actual over-voltages it produces.

Over-voltages can be produced on both the line side and the pply side of the circuit-breaker. These are liable to be greatest when the line-side capacitance is large compared with that on the supply side.

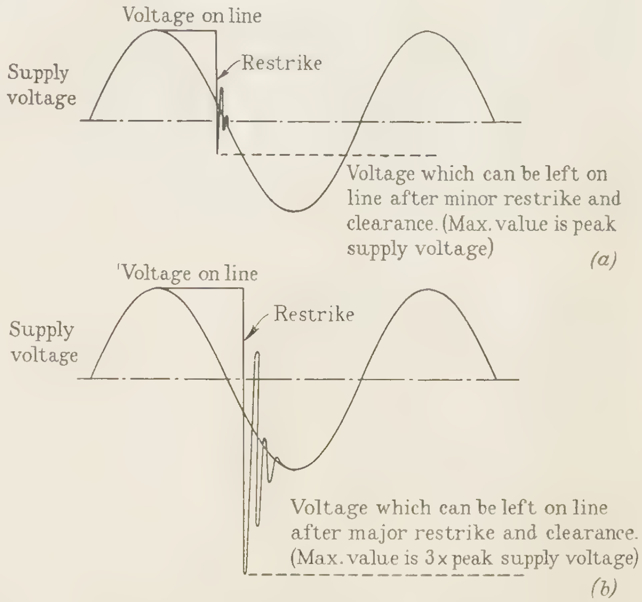



Fig. 9.—Comparison between possible over-voltages with minor and major restrikes when breaking charging current.
(*a*) Minor restrike. (*b*) Major restrike.

As far as shock pressures are concerned an intermediate value of capacitance on both sides of the circuit-breaker (and consequently a ratio approaching unity) is likely to be worst; this will permit a sudden heavy discharge in an oil-filled arc-control pot. When larger charging currents are being broken the initial arcing (before major restrikes can occur) may be sufficient to create a gas cushion inside the arc-control pot, and this will absorb the shock.

A factor which plays an important part in the production of over-voltages and shock pressures is the inductance of the line. It is doubtful whether the effects of distributed capacitance and inductance can be reproduced, even approximately, by a lumped capacitance only. Other factors which must be taken into account are the method of earthing and whether tests are being done single-phase or 3-phase.

It is beyond the scope of the paper to discuss the breaking of line-charging currents in greater detail. In testing stations equipped with capacitors and reactors to simulate overhead lines and cables, it is possible to make tests which in the magnitude of the over-voltages set up and the severity of the impulse pressures are comparable with those on actual networks. However, the closeness of this relationship is not easy to assess, and it is suggested that proving tests be made on lines similar to those followed for magnetizing-current switching; i.e. circuit-breakers for test should be checked against the characteristics of a similar circuit-breaker whose performance, when breaking charging currents under representative conditions both on actual networks and in the testing station, is known.

Where large capacitor banks are not available in a testing station a good idea of the number of major restrikes likely to occur can be obtained by switching even small charging currents of a few amperes, and from this the probable over-voltages may be deduced. However, no indication of shock pressures can be found in this way.

### (5.5) The Switching of Capacitors[21]

The use in service of large banks of compensating capacitors, particularly shunt capacitors, is increasing, and attention must be given to this problem.

Where testing stations are equipped with large banks of capacitors it is possible to make fully representative tests. Two points of particular importance stand out. First, it is necessary to allow for conditions where capacitors connected to the supply side are similar in size to those being switched or even larger. Secondly, it is important so to match the source inductance to the load capacitance that when the latter is connected the steady voltage rise is not excessive, say not more than 20%.

## (6) TESTING FACILITIES

### (6.1) Testing Stations

The range of tests required to prove circuit-breakers adequately has been covered, and some indication has been given of the facilities which exist and the limitations which they impose on the proving of large high-voltage circuit-breakers. It became apparent to the authors that, although testing-station output could never hope to keep up with system fault capacity, some action was essential to narrow the gap. A study was made of the various possibilities, and the conclusion was reached that satisfactory proving of the breaking and making capacities of large high-voltage circuit-breakers could be based on single-phase unit tests. On this basis a new testing station was built capable of proving the largest single unit which is likely to be made in the foreseeable future. This station is described in a companion paper.[29]

### (6.2) Field Testing

In the United States, field tests, i.e. tests on actual power systems, have long played a prominent part in proving large circuit-breakers, and more recently, with the opening of the Fontenay Testing Centre,[27] such tests have received added emphasis in France and elsewhere on the Continent. While wishing to acknowledge in every way the value of field tests, it is important to assess them at their true worth and to recognize that they do not provide a complete answer, either in respect of development or proving tests. Here we need deal with the reasons for this only in so far as they apply to proving tests: first, the limitation imposed by the comparatively inflexible arrangement of a service network will usually prevent the full range of tests from being adequately covered; and secondly, there are the limitations imposed by the fact that in most cases the conditions of circuit severity (particularly r.r.r.v.) are only moderate and will often be less severe than those in other locations.

It will be apparent from the foregoing that, as testing-station tests and field tests both have their limitations, which are usually different, the two together can give the complete answer. As testing-station tests are more convenient, they should form the main basis for development and proving. The use of field tests would thus be to check the extrapolation which will always be needed for large high-voltage circuit-breakers, from the tests at testing stations, and for correlating actual system conditions with the arrangements at the testing stations.

To obtain the greatest benefit from field tests they should be made not at one centre but at a number of selected points. At such points the provision of firm platforms, where circuit-breakers could be erected, and adequate means of access would be a great advantage.

## (7) CONCLUSIONS

(7.1) The standard proving tests provide a good basis for the test programme, but it is necessary to make a number of additional tests to cater for features not included in standard specifications and to allow for the individual characteristics of the different types of circuit-breaker. This applies particularly to large circuit-breakers.

(7.2) All aspects of a circuit-breaker's performance must proved and not merely a few specialized aspects (see Section

(7.3) Service conditions provide the only proper basis testing (see Section 3).

(7.4) The proving of circuit-breakers could be improv by changes in, and additions to, existing standard tests, example:

(*a*) More precise definition of the asymmetrical test (see Section 3.1).
(*b*) Increase in the minimum recovery voltage permissible large circuit-breakers (see Sections 3.2.1. and 3.2.2).
(*c*) Specification of standard values of the r.r.r.v. (see Section 3.2
(*d*) Revision of test voltages for single-phase tests on large hi voltage circuit-breakers (see Section 4.1).
(*e*) Larger tolerances in the currents when testing large circu breakers (see Section 4.4).
(*f*) Inclusion of at least one make-break test (see Section 4.7).
(*g*) Inclusion of single-phase and/or phase-to-phase tests ( Section 4.9).
(*h*) Testing large high-voltage circuit-breakers under out-synchronism conditions (see Section 4.10).
(*j*) Inclusion of a 5% test duty (see Section 4.11).

(7.5) The most acceptable solution of the problem of testi large circuit-breakers whose short-circuit rating is larger th the testing plant available is likely to be found in single-pha unit tests (see Sections 4.1 and 4.2). Synthetic tests have limited application for making-capacity tests, but their valid for proving purposes is doubtful (see Section 4.3).

(7.6) Consideration should be given to the standardization tests (correlated with system conditions) required to pro normal switching duties, such as load switching (see Section 5. transformer magnetizing-current switching (see Section 5.2), a live-line switching (see Section 5.4); these are at present n covered by any standard test rules (see Section 5).

(7.7) Tests at testing stations and in the field are comp mentary rather than alternative, and extensive use should made of both for complete proving (see Section 6.2).

(7.8) Examples of typical test schedules for two widely d similar circuit-breakers are given in Section 10.

## (8) ACKNOWLEDGMENTS

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## (10) APPENDIX

**Table 2**

EXAMPLE OF TEST SCHEDULE FOR TWO-BREAK CIRCUIT-BREAKER RATED AT 5 000 MVA ARRANGED FOR HIGH-SPEED AUTO-RECLOSING

| % rated short-circuit current | Duty cycle | No. of phases | Test voltage | Notes |
|---|---|---|---|---|
| 100% | 3-sec | 3 | 440 volts | Short-time current test. |
| 5% | B–3–B–3–B | 3 | Full rated | |
| 10% | B–3–B–3–B | 3 | Full rated | |
| 39% | B–3–B–3–B | 3 | Full rated | Max. 3-phase plant output. |
| 71% | B–3–B–3–B | Single | Full rated (with 1·5 factor) | Max. single-phase output (with 1·5 factor). |
| 100% (symmetrical) | B–3–B–3–B | Single | Full rated (phase value) | May be supplemented with unit tests. |
| 100% | M–3–M | Single | Full rated | |
| 100% (asymmetrical) | B–3–B–3–B | Single | Full rated (phase value) | Subject to proposed new conditions. May be supplemented with unit tests. |
| 100% (symmetrical) | B–3–B–3–B | Single (one unit) | Full unit test voltage | Supplementary unit test if adequate full-scale tests are impossible on complete circuit-breaker. |
| 100% (asymmetrical) | B–3–B–3–B | Single (one unit) | Full unit test voltage | Supplementary unit test if adequate full-scale tests are impossible on complete circuit-breaker. |
| 100% make, 90% break | MB–3–MB | Single | Full rated (phase value) | Not required if auto-reclosing tests made. |
| 10% | B–*t*–MB | 3 | Full rated | |
| 100% | B–*t*–MB | Single | Full rated (phase value) | Current may be low on second break. |
| 25% | B–3–B–3–B | Single | Double rated phase voltage | Out-of-synchronism test. |
| — | 6 shots | 3 or single | Full rated | *Steady transformer magnetizing current. |
| — | 6 shots | 3 or single | Full rated | *Transient transformer magnetizing current. |
| — | 6 shots | 3 or single | Full rated | *Selected charging current. (Low *C* on source side.) |
| — | 6 shots | 3 or single | Full rated | *Selected charging current. (Source *C* = Line *C*) |

* These tests will be determined largely by the equipment available at the testing station.

**Table 3**

Example of Test Schedule for Single-Break Air-Break Circuit-Breaker

| % rated short-circuit current | Duty cycle | No. of phases | Test voltage | Notes |
|---|---|---|---|---|
| 100% | 3-sec | 3 | 440 volts | Short time current test. |
| 5% | B–3–B–3–B | 3 | Full rated | 80% reactance on load side of circuit-breaker. |
| 10% | B–3–B–3–B | 3 | Full rated | |
| 30% | B–3–B–3–B | 3 | Full rated | |
| 60% | B–3–B–3–B | 3 | Full rated | |
| 100% (symmetrical) | B–3–MB–3–MB | 3 | Full rated | |
| 100% (asymmetrical) | B–3–B–3–B | 3 | Full rated | Subject to proposed new conditions. |
| 10% | B–3–B–3–B | 3 | Full rated | Test connections reversed. |
| 100% (asymmetrical) | B–3–B–3–B | 3 | Full rated | Test connections reversed. |
| 100% (symmetrical) | B–3–B–3–B | 2 | Full rated | Test to check unbalanced magnetic forces. |

[The discussion on the above paper will be found on page 716.]

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Paper No. 1736 S
Dec. 1954

# A NEW TESTING STATION FOR HIGH-POWER CIRCUIT-BREAKERS

By J. CHRISTIE, M.I.Mech.E., H. LEYBURN, B.Sc.(Eng.), Members, and
R. W. FENN, M.Eng., A.M.I.Mech.E., Associate Member.

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SUMMARY

The paper describes the general considerations that led to the uilding of a new testing station for high-power circuit-breakers, and ves particulars of its main technical features. The 3-phase output the generator voltages, i.e. up to 22 kV, is adequate for full-scale sting of circuit-breakers at these voltages. At higher voltages, and rticularly above 66 kV, the provision of equipment for full-scale phase testing of the largest circuit-breakers could not be justified onomically; and since circuit-breakers for these voltages can be sted satisfactorily as single-phase units, special efforts were made to otain high single-phase outputs. This was obtained by a combinaon of features described in the paper. The outputs so obtained, up a voltage corresponding to a rated (3-phase) voltage of 380 kV, ill enable full-scale single-phase tests or unit tests to be made on most any circuit-breaker likely to be required in the foreseeable ture.

## (1) INTRODUCTION

Short-circuit testing stations have been firmly established for any years, and the work done in them has contributed greatly progress in the art of circuit-breaking. The forerunner of the ort-circuit testing station described in the paper was comissioned in 1929,* and was thus the first in Great Britain. ith the extensions made later it was one of the largest stations the world, having a symmetrical 3-phase output of 1 600 MVA to 22 kV and an equivalent symmetrical 3-phase output, otained single-phase, of about 1 100 MVA at higher voltages.

In recent years the demand for circuit-breakers with higher ort-circuit ratings had been growing so rapidly that the ailable test facilities were outstripped, and the limitations us imposed made it difficult always to determine the most onomical design. It was realized that to extend the existing cilities would be a costly procedure, and before deciding to so, possible alternatives were investigated, namely field sting and synthetic testing. The following conclusions were rived at:

Field testing is primarily useful for the final proving of circuit-breakers under the specific conditions of circuit severity encountered at the selected points in the power system in which the tests are being done, and also for certain supplementary tests, such as the switching of lightly-loaded lines. It does not, however, provide the range and flexibility necessary for research and development work.

Synthetic testing, as developed at present, is useful for some research tests. The results cannot, however, be accepted as reliable proof of the performance of large circuit-breakers.

Thus neither field testing nor synthetic testing is a satisfactory ternative for a short-circuit testing station with high output, hich makes it possible for research, development and proving sts to be done under the widely varying conditions likely to be et with in service. It was therefore decided to build a new sting station based upon the existing station and making as uch use of the available equipment as possible.

The first problem was to determine the output required from the new station. A preliminary survey showed that the output of the existing plant at the generator voltages, i.e. up to 22 kV, was adequate for full-scale testing of nearly all circuit-breakers at these voltages; at higher voltages, however, and particularly at those above 66 kV, the provision of equipment for full-scale 3-phase testing of the largest circuit-breakers could not be justified economically.

It was therefore decided to provide a testing station with sufficient output to enable full-scale single-phase tests or unit tests to be made on almost any circuit-breaker that will be needed to meet system requirements in the foreseeable future.

A further aim that was kept in view was the speeding up of testing, necessitated by the volume of research, development, and proving work, which had greatly increased since the original testing station was built.

The authors believe that the new facilities will enable the designer to work with greater freedom and make it possible for better circuit-breakers to be produced.

## (2) OUTPUTS

The available output of the station with substantially full recovery voltage varies according to the voltage range, but with a few minor exceptions it is almost constant within each range, provided the optimum voltages are used. These, in general, include the standard voltages used in Great Britain, together with some of the more common voltages used elsewhere. The outputs, based on the currents one cycle after the initiation of the short-circuit, are as follows:

(*a*) Up to 22 kV: 3-phase output (using two generators only): 2 000 MVA.

(*b*) 33–275 kV: 3-phase output: 1 500/2 000 MVA.

(*c*) 66–380 kV: equivalent 3-phase outputs, obtained single-phase: 3 200 MVA (with recovery voltage $1 \cdot 5V/\sqrt{3}$); 4 800 MVA (with recovery voltage $V/\sqrt{3}$).

It needs to be stressed that these figures are based on symmetrical currents. The asymmetrical outputs, with the same symmetrical a.c. components, are much higher, and any circuit-breaker with a short-circuit rating up to the full symmetrical output of the station can be tested both at the rated symmetrical current and at the larger rated asymmetrical current, in accordance with I.E.C. and British Standard requirements.

## (3) GENERAL CONSIDERATIONS

### (3.1) General

The considerations underlying the overall design of the new testing station can best be followed by reference to Fig. 1, which is a simplified single-line schematic of the electrical layout of the old and new testing stations combined. The old station contained two generating sets, each having its own master circuit-breaker, short-circuit reactors and resistors and other associated equipment. There were also 12 step-up power transformers which enabled tests to be done up to 132 kV, and by using a cascade connection, up to 220 kV with much reduced

* CLOTHIER, H. W.: "The Hebburn Short-Circuit Testing Plant," *Electrical Review*, 30, **106**, p. 996.

The authors are with A. Reyrolle and Co. Ltd.

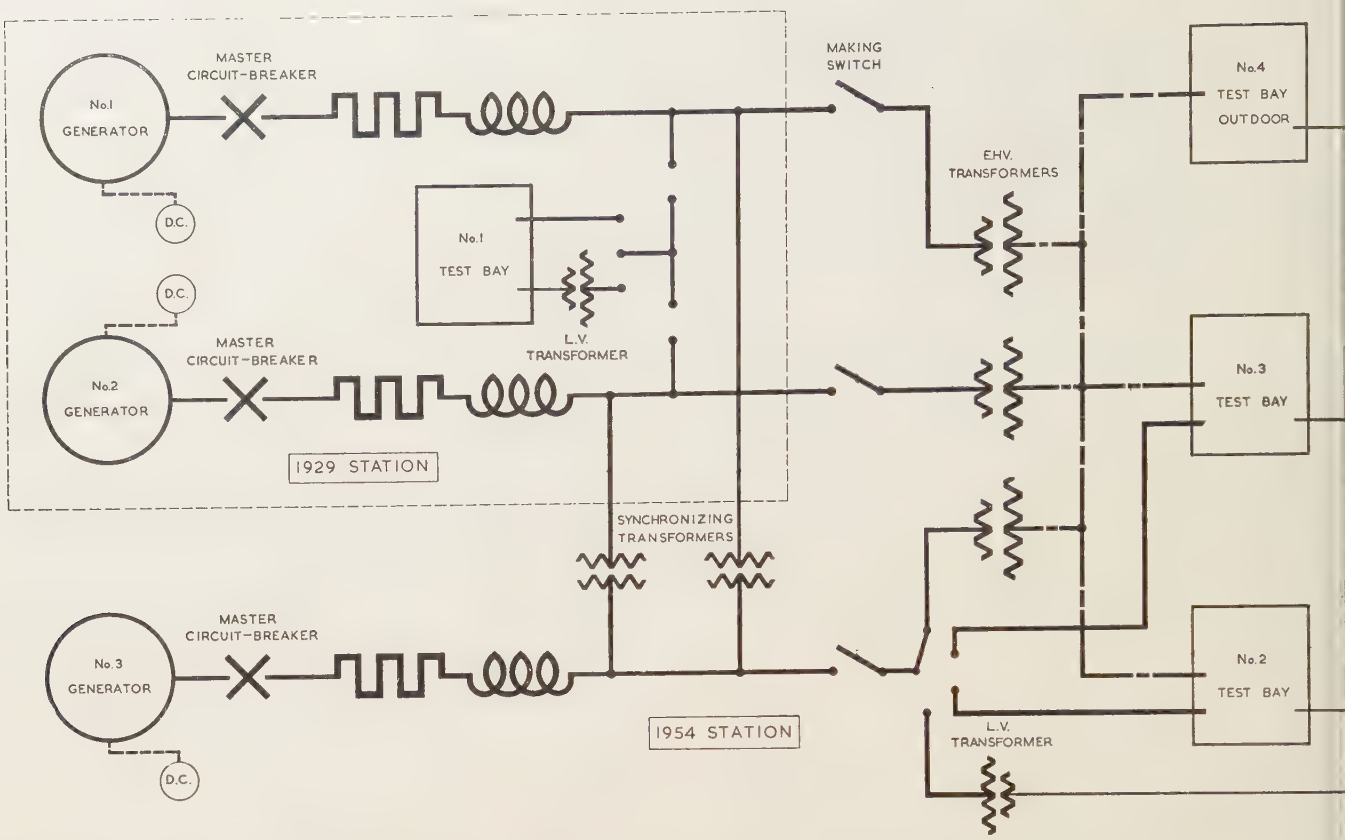



**Fig. 1.**—Electrical layout of old and new testing stations. Simplified single-line schematic.

Generator voltage.
Extra high voltage.
Low-voltage a.c.
Low-voltage d.c.

output. In addition there was a low-voltage power transformer, stepping down from the generator voltage to lower voltages suitable for short-time current tests and short-circuit tests of circuit-breakers with rated voltages of 1 500 volts and below. All this equipment was connected to an indoor test-bay and to an improvised outdoor test area, not shown in Fig. 1.

Because the most convenient site for the new testing station was about 300yd from the old one, it was necessary to decide whether to move the existing main equipment, bearing in mind that to obtain the highest outputs at voltages above the generator voltages all the generators and step-up power transformers would have to be used together. The transformers were moved to the new site and installed close to the new transformers mentioned below. It was found, however, that the cost of transferring the two existing generators would be very high. Investigations showed that the generators could be connected to the new testing station by means of cables, with little loss of power, and that the effect of the cable capacitance on the rate of rise of restriking voltage on the e.h.v. side of the power transformers would be less than 5%. It was therefore decided to leave the two generators, together with their associated equipment, at the old testing station, which now serves a dual purpose. First, tests at the generator voltages, i.e. up to 22 kV, continue to be done there, and secondly it provides additional power to the new testing station for tests with the highest outputs.

The new generator and transformer equipment installed at the new testing station consists of a generator (No. 3) and of three single-phase power transformers much larger than the old ones, so arranged that they can be used in conjunction with them.

The two existing generators,* which were over 20 years o[ld] and had been subjected to about 40 000 short-circuit tests eac[h] had to be rewound to improve their insulation security; a[nd] while this was being done, their short-circuit output was increas[ed] by a modification of the winding arrangement. This broug[ht] the outputs at generator voltages, using two generators onl[y] up to values which are fully adequate for the testing of circu[it-] breakers at these voltages.

At higher voltages, however, the problems associated wi[th] the attainment of the highest outputs, particularly single-phas[e] were more complex. In the following Sections an account [is] given of how these problems were solved and of the resulti[ng] operating conditions.

### (3.2) Parallel Running of Generators

To obtain the highest outputs it is necessary to use all thr[ee] generators together. It is undesirable to parallel them direct[ly] because of the very large currents which might flow in the eve[nt] of a fault in the generator circuit. The scheme adopted involv[es] paralleling on the e.h.v. side of the power transformers and t[he] provision of auxiliary transformers to ensure synchronism pri[or] to the application of the short-circuit. In breaking-capaci[ty] tests the circuit is prepared with all connections complet[e] except the making switches, which are closed last to apply t[he] short-circuit. In making-capacity tests, the making switch[es] are closed first, thereby energizing the power transformers [a] few cycles before the closing of the circuit-breaker under te[st].

* EASTON, V.: "Some Factors affecting the Design of Alternators for Switchg[ear] Testing," *Journal I.E.E.*, 1943, 90, Part II, p. 202.

and after this has closed, the circuit is broken by opening the master circuit-breakers.

When it is intended to run the generators in parallel, using the synchronizing transformers, they are connected together, energized by remanent magnetism only. The field circuits are then closed, and as the excitation is raised to the normal value the generators pull into step by virtue of the power transferred through the synchronizing transformers. The reactive component of this power is measured and kept as near zero as possible by adjusting the excitation by hand. A further increase in exciting current, required when the generators are run in parallel on over-excitation, is obtained automatically; this is dealt with in Section 3.4.

### (3.3) Control of Asymmetry

When the circuit-breaker under test is required to break a symmetrical current, it has been usual in the past so to time the operation of the circuit-breaker that it opened a few cycles after the instant of application of the short-circuit. The effect of this was that a certain amount of the generator output was lost owing to its natural decrement. This loss can be avoided to a great extent with single-phase short-circuits by controlling the instant of application of the short-circuit and hence the degree of asymmetry, thus making it possible for symmetrical tests to be made during the sub-transient period. This has been accomplished by designing the making switches to be accurate enough for point-on-wave closing. An additional advantage is that accurate control of the degree of asymmetry enables the number of shots to be reduced because the element of chance in obtaining the desired asymmetry is eliminated.

The desired point on the voltage wave at which the making switch closes is selected by a small constant-voltage a.c. generator, mechanically coupled to one of the main generators, which feeds a voltage through a phase-shifter and peaking circuit to a thyratron grid. Firing of the thyratron occurs at the selected point of the voltage wave; it is initiated by the voltage pulse from the peaking circuit after the appropriate contact on the test-sequence controller has closed.

### (3.4) Over-Excitation

To obtain a high current at a high recovery voltage and thereby virtually to increase the available output of the generator it is possible to use one of two methods of exciting a short-circuit testing generator above normal: the first is "super-excitation," a method that has been used previously and is described elsewhere;* the second, which has been termed "over-excitation," is used in the testing station under consideration.

When a normally-excited generator is short-circuited the a.c. component of the current decreases as illustrated in Fig. 2, and if the short-circuit is cleared when the current has fallen from $I_0$ to $I_f$ (i.e. at the instant F in the Figure), the recovery voltage at the generator terminals expressed as a fraction of the voltage before the short-circuit is $I_f/I_0$. The rate of decrease of the current during the sub-transient period can be reduced to some extent by means of a rotor damping winding, but nothing further can be done to alter the shape of the sub-transient current characteristic. The reduction in current during the transient period, however, which is determined mainly by the demagnetizing effect of the short-circuit current (i.e. by armature reaction), can be compensated for completely by injecting into the field winding sufficient exciting current to counteract the effect of the armature reaction. This is the principle of super-excitation, which has been previously applied to short-circuit testing generators.

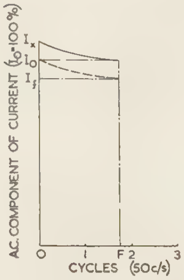



**Fig. 2.**—Short-circuit generator currents with normal and over-excitation.

——— Over-excitation.
- - - - - Normal excitation.

Although it has been described in detail elsewhere, it will be described briefly here to provide a comparison with over-excitation.

In a super-excited generator, as soon as the short-circuit has been applied, a large current is forced through the rotor winding to counteract the demagnetizing effect of the armature reaction, thereby causing the short-circuit current to rise again after the initial drop, as shown in Fig. 3. The circuit-breaker under test opens at the instant $F_3$ after the current has risen again to its initial value, about 20 cycles after the application of the short-circuit at the instant $F_1$.

The excess exciting current required to overcome the demagnetizing effect of the short-circuit current is very large, and it was calculated that to apply super-excitation to generator No. 3 an exciter capable of delivering 25 MW would have been required; such a machine would have been roughly as big as the generator itself.

Superficially over-excitation is similar to super-excitation, in that it involves boosting the field current, but the principle is fundamentally different. Whereas with super-excitation the field current is boosted at the instant of application of the short-circuit in order to overcome the armature reaction during the short-circuit, with over-excitation it is boosted *well before* the short-circuit is applied, with the object of raising the initial voltage of the generator to a value higher than normal. As shown by the upper curve of Fig. 2, with over-excitation the current decreases after the application of the short-circuit (at the instant $F_1$ of Fig. 3), but since its initial value is higher, the current broken by the circuit-breaker under test (at the instant $F_2$ of Fig. 3) can be made equal to the full short-circuit current $I_0$. The power required to raise the generator voltage from its normal value, corresponding to $I_0$, to a value corresponding to $I_x$ is very much less than that required for super-excitation, first because the over-excitation is applied when the generator is on open-circuit and has not to overcome the powerful demagnetizing effect of the short-circuit current, and secondly because the time during which over-excitation takes place is relatively long. The time chosen for the generators under discussion is between 2 and 3 sec. The power required to provide over-excitation for generator No. 3 is of the order of 1 MW, as compared with 25 MW for super-excitation. Apart from the fact that the d.c. machine and the building which houses it can be much smaller and less costly than those for super-excitation, the ancillary equipment presents no difficult problems, as it does with super-excitation, and the operation of the machine is simpler.

Over-excitation has other important advantages:

(*a*) It enables tests with asymmetrical currents to be made without difficulty, because the circuit-breaker under test may be timed to clear the short-circuit current during the sub-transient period, and by using a point-on-wave making switch (see Section 3.3) asym-

* Easton, V.: "Some Factors affecting the Design of Alternators for Switchgear Testing," *Journal I.E.E.*, 1943, 90, Part II, p. 202.

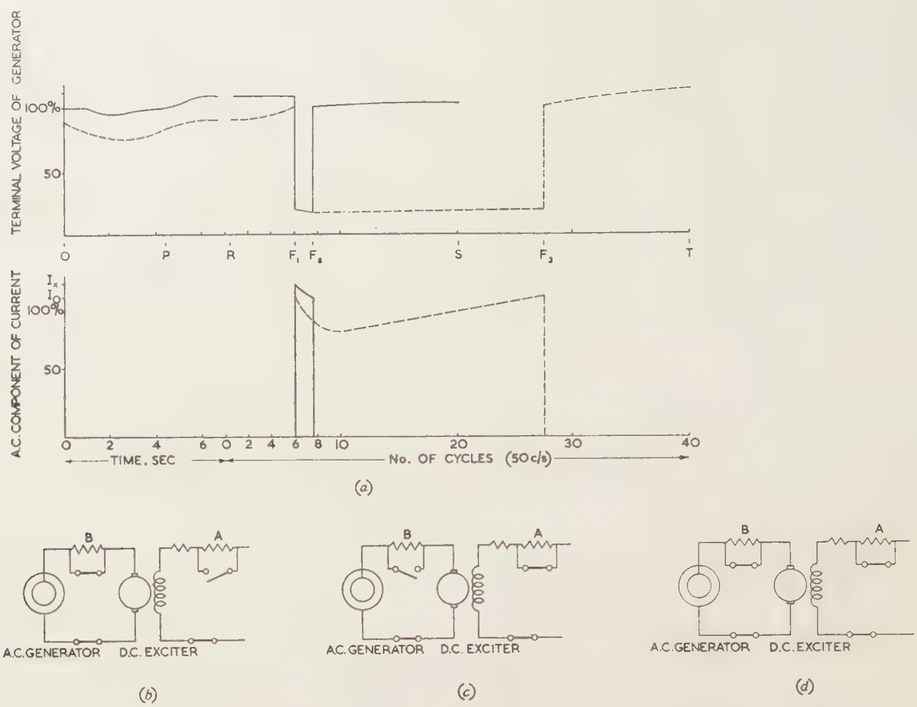



**Fig. 3.**—Comparison of over-excitation and super-excitation.

(*a*) ——— Over-excitation.
- - - - - Super-excitation.

The short-circuit is applied at $F_1$. The circuit-breaker under test clears at $F_2$ with over-excitation and at $F_3$ with super-excitation.

(*b*) Condition up to period O.
(*c*) Condition during period OP for over-excitation and OR for super-excitation.
(*d*) Condition during period PS for over-excitation and RT for super-excitation.

metrical short-circuit currents can be obtained with certainty; with super-excitation, on the other hand, clearance takes place about 20 cycles after the initiation of the short-circuit, and by then the current is completely symmetrical.

(*b*) Parallel operation of generators using over-excitation presents no difficulty, because the time during which over-excitation is applied is relatively long and the timing is not critical.

(*c*) Over-excitation can be used for increasing the output voltage of the interconnected windings of a generator, as required for the "U-connection"—a method evolved for increasing the single-phase output at standard test voltages, described in Section 3.5.

Other points relating to over-excitation which are worth mentioning are as follows: Any normal short-circuit testing generator is easily capable of withstanding for a few seconds at a time the increased voltage (up to 20% higher than normal) which occurs during the over-excitation period. With most short-circuit generators, however, it is inadmissible to exceed the current corresponding to a short-circuit across the generator terminals at normal excitation, because the bracing of the end windings is not designed to withstand currents greater than this; and thus the benefits of over-excitation cannot be obtained at the generator voltages. At higher voltages, however, the added reactance of the step-up power transformers prevents the short-circuit current from reaching a value corresponding to a dead short-circuit across the generator terminals, and it is under these conditions that over-excitation is used to its best advantage. Thus over-excitation fitted in with the aim, mentioned earlier in the paper, of obtaining the highest possible output at the higher voltages, the output at the generator voltages being already adequate.

The increase in field current required for over-excitation or for super-excitation is obtained by switching resistors in the exciter and generator field circuits, and the switching sequence, which is similar for both, will now be described briefly. The switching (see Fig. 3) takes place in two stages, and is controlled automatically. In the preliminary stage [Fig. 3(*b*)], when the machine is set by hand in readiness for the first stage of field boost, resistor A in series with the exciter field windings is in circuit and resistor B in series with the generator field winding is short-circuited. In the first automatic stage of boost [Fig. 3(*c*), resistor A is short-circuited and resistor B is open-circuited. This builds up the voltage across the exciter ready for the next stage but prevents exciting current from being forced through the generator field winding. In the second stage [Fig. 3(*d*)], resistor B is also short-circuited and thus the generator field is boosted. The timing and the effects of the boost are shown in Fig. 3 both for over-excitation and for super-excitation.

### (3.5) Method of Increasing Single-Phase Output at Standard Voltages (U-Connection)

As stated in Section 3.4 it is possible to increase the available output of a generator by over-exciting it, so that its open-circuit voltage just prior to the application of the short-circuit is higher than normal. In the testing station under consideration such an increase is required only at voltages obtainable through step-up power transformers, the ratios of which are fixed by considerations such as normal 3-phase and single-phase testing at standard voltages. To make the best use of these transformers and to obtain standard testing voltages on the e.h.v. side, it is necessary to apply one of the standard generator voltages, namely 11 kV or 22 kV, to the primary windings of the power transformers (see Sections 4.1 and 4.6).

If, with these considerations in mind, it is desired to increase the available output of a generator-transformer unit, this can be done only by the installation of more plant or by an arrangement of the generators in such a way that their internal reactance

at 11 or 22 kV is reduced. An examination of the second alternative, which is by far the more economical, showed that the desired result could be obtained by the use of a novel connection of the generator windings, now known as the U-connection, together with over-excitation. The U-connection is applicable to generators with two separate windings per phase, and can best be understood by comparison with a conventional single-phase connection.

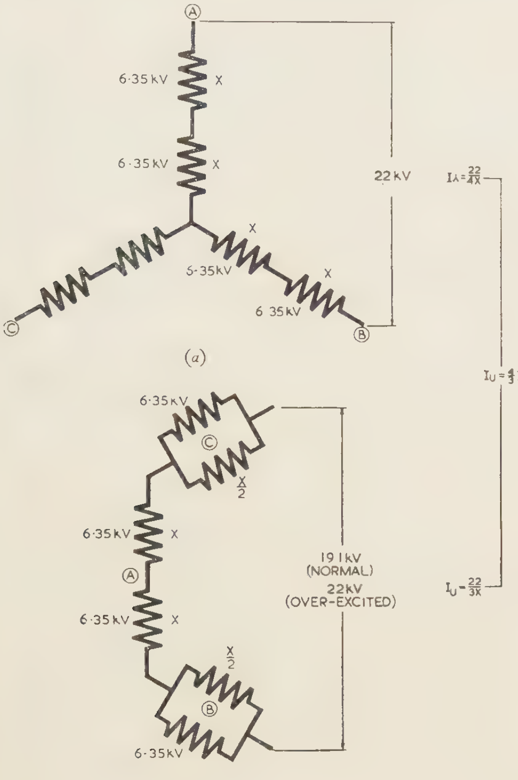



**Fig. 4.**—Derivation of U-connection for generator.
(*a*) Normal 22 kV single-phase connection.
(*b*) 22 kV U-connection.

Fig. 4(*a*) shows the conventional method of connecting a generator to the primary winding of a step-up power transformer to obtain a single-phase e.h.v. test supply. The two windings of each phase of the generator are connected in series, and so if each winding has a reactance $X$, and the voltage at the output terminals is 22 kV, the maximum output of the generator is $22^2/4X$ MVA. In the U-connection, illustrated in Fig. 4(*b*), the two windings of one phase are connected in series; they are then in turn connected in series with the parallel-connected windings of the two other phases. The voltage at the terminals under the same conditions of excitation as in Fig. 4(*a*) is 19·1 kV, but the reactance of the winding arrangement is only $3X$.

By over-exciting the generator by 15% and thereby raising the output voltage to 22 kV, the maximum output is equal to $22^2/3X$ MVA; i.e. for the same voltage, the MVA output of the generator with the U-connection is one-third higher than with the conventional connection. Hence, if the boosted output voltage of the U-connected generator is applied to the primary winding of a step-up power transformer, the MVA output on the e.h.v. side, obtained at a standard testing voltage, will also be higher.

The above calculation is based on the assumption that the reactance of each winding of the generator is the same with the U-connection as with the conventional single-phase connection. In practice, however, it is usually lower, depending upon the magnitude and distribution of current in the generator windings, and thus a correspondingly greater increase in single-phase output is obtained.

### (3.6) Rate of Rise of Restriking Voltage

The connections between the two generators and the test bay at the 1929 station are short and have comparatively little capacitance, and this enables tests to be made at voltages up to 22 kV up to the maximum output of the two generators at high inherent circuit frequencies.

As regards tests at higher voltages, which involve the power transformers at the 1954 station, the capacitance on the e.h.v. side has been kept to a minimum. The inherent circuit frequencies and the corresponding rates of rise of restriking voltage obtained with all the power transformers in circuit are shown by curve (*a*) of Fig. 5 for a single-phase test voltage of 152/160 kV.

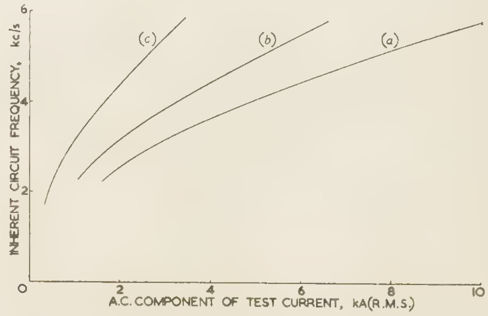



**Fig. 5.**—Circuit frequencies for 152/160 kV single-phase test connection.
(*a*) 15 transformers.
(*b*) 10 transformers.
(*c*) 5 transformers.
The r.r.r.v. can be calculated from the formula $2fV\sqrt{2} \times d$.
where $f$ = Inherent circuit frequency.
$V$ = R.M.S. test voltage.
$d$ = Amplitude factor.

For tests at lower MVA outputs it is possible to disconnect some of the transformer units, thereby increasing the circuit frequency, and this is illustrated by curves (*b*) and (*c*) of Fig. 5. These curves show that for a 275-kV system, for which 160 kV is the phase-to-neutral voltage, the system requirements in respect of r.r.r.v. can be more than satisfied by either full-scale or unit tests, except possibly at the test duties of 30% of the circuit-breaker rating and below (see Section 3.2.3 of the paper* by Messrs. Christie, Leyburn and Bird).

The measured circuit frequencies at 152/160 kV agree within fairly close limits with the calculated circuit frequencies shown in Fig. 5. Measurements at other test voltages are proceeding, and if, as is anticipated, equally close agreement is obtained, testing at the other voltages will present no greater difficulty in respect of r.r.r.v. than at 152/160 kV.

### (3.7) Insulation Levels

The insulation levels at the generator voltages, i.e. up to 22 kV, which have been in existence for some considerable time have been found to be satisfactory. To protect the generators against over-voltages, an arc-gap in series with a resistor is connected between each phase and earth; it is set to flash over at a voltage of 35 kV (r.m.s.), and the resistor passes approximately 400 amp at 22 kV.

At higher voltages careful consideration had to be given to

* CHRISTIE, J. LEYBURN, H., and BIRD, J. F.: "Proving the Performance of Circuit-Breakers, with particular reference to those of Large Breaking Capacity," see page 697.

the insulation level to be adopted; and this was based almost entirely on the ability of the high-voltage connections to withstand the appropriate impulse voltages to earth. The insulation between phases, as determined by the inter-phase clearances, is well in excess of that to earth.

The highest output voltage to earth of the new power transformers is 160 kV (r.m.s.), corresponding to 226 kV peak. With this as the starting point, the impulse-withstand levels adopted at various places were as follows:

| | |
|---|---|
| E.H.V. connections in indoor test bays .. .. .. | 600 kV |
| E.H.V. connections in outdoor test bay, with the possibility of an increase at a later date from 800 to 1 000 kV | 800 kV |
| E.H.V. power transformers .. .. .. .. .. | 1 250 kV |

These insulation levels make it possible for all high-voltage circuit-breakers to be tested adequately. The grading of the insulation levels provides over-voltage protection for the e.h.v. power-transformer windings without the addition of special protective devices.

### (3.8) Physical Arrangement

There are two indoor test bays of conventional design, and one outdoor test bay capable of accommodating a complete 380-kV 3-phase circuit-breaker. In contrast to most other testing stations, the circuit-breakers to be tested are brought into the test bays through the rear, thus making it possible to obtain a neat and convenient layout.

## (4) MAIN EQUIPMENT

### (4.1) Generators

The frame size of the new generator, No. 3, is 60 MVA, and its short-circuit power is approximately 2 000 MVA. The corresponding values for each of the two old generators are 50 MVA and 1 350 MVA. Thus the total short-circuit power of all three generators is approximately 4 700 MVA. At generator voltages, however, the output of only two generators is used, as stated in Section 2, since it is adequate for testing standard circuit-breakers at these voltages.

The generators are driven at 3 000 r.p.m. by 1 000-h.p. induction motors which are disconnected from the supply prior to the actual tests. Each generator has two windings per phase, and thus there are four basic voltages, namely 6·35, 11, 12·7 and 22 kV.

The exciter for No. 3 set is provided with a 12·5-ton flywheel and is driven at 750 r.p.m. During normal excitation it has an output of about 600 amp, and this is increased to 1 500 amp during over-excitation by the automatic short-circuiting of a series resistor (see Section 3.4).

The exciters for generators Nos. 1 and 2 have a common shaft and a 5-ton flywheel, and are driven at 1 500 r.p.m. Each of the two exciters has an output of 300 amp for normal-excitation purposes, which can be increased to 650 amp during the over-excitation period.

### (4.2) Master Circuit-Breakers

Each generating set is provided with its own master circuit-breaker, capable of breaking the full output of the generator. The circuit-breakers are of the metalclad draw-out type, fully phase-separated, and fitted with Turbulator arc-control devices.

### (4.3) Reactors and Resistors

The reactors used to control the magnitude of the short-circuit current are air-cored, and consist of six stacks per phase with three coils per stack. The total reactance per phase is about 25 ohms, and intermediate values can be obtained by combinations of tappings and series-parallel connections. In the design of the tap-changing links, particular attention has been paid to the speed with which changes can be made.

The reactors for controlling currents in the load-current range are iron-cored, and are adjustable to give currents from 5 to 250 amp.

The resistors, which are primarily for the control of power factor in short-circuit tests, are of the metal-grid type and are also provided with tappings.

### (4.4) Synchronizing Transformers

The two synchronizing transformers, used to maintain the three generators in synchronism prior to the application of a short-circuit, are connected between generators Nos. 1 and 3 and generators Nos. 2 and 3. They have a reactance of 6% based on a nominal rating of 500 kVA. With the generators over-excited to 22 kV on the U-connection, which gives the largest difference in iron losses, sufficient power is transferred to keep the phase angle between generators down to less than five electrical degrees during the excitation period.

### (4.5) Making Switches

For each generating set there are three single-pole making switches (see Fig. 6) permanently coupled together, i.e. nine

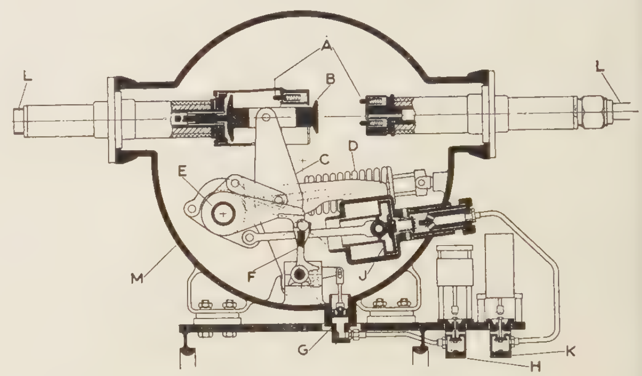



**Fig. 6.**—Interior of making switch.

A Fixed contacts.
B Moving contact.
C Contact lever.
D Operating spring.
E Main shaft.
F Tripping latch.
G Tripping-relay cylinder.
H Trip valve and magnet.
J Piston for charging operating spring.
K Charging valve and magnet.
L Terminals.
M Pressure tank.

single-pole units in all. Their duty is to apply the short-circuit and they close at a selected point on the voltage wave (see Section 3.3) with a tolerance, including that of the initiating equipment, of $\pm 10$ electrical degrees. To achieve the necessary accuracy, all moving parts have been kept as light as possible and friction has been reduced to a minimum. Furthermore, in order to reduce the effect of pre-arcing when closing, each pole is made to operate in compressed air at 150 lb/in$^2$. The switches are operated by springs charged by compressed air; and each 3-pole switch can be operated separately, or all nine poles can be ganged mechanically by means of clutches.

### (4.6) Power Transformers

The twelve 11/38-kV single-phase power transformers transferred from the old to the new station can be connected in pairs to give an output voltage of 76 kV phase-to-earth.

The three new single-phase transformers have alternative primary voltages of 11 and 22 kV, and secondary voltages of 38, 76, 114 and 152 kV phase-to-earth; these can be increased by 5% with corresponding increase in flux density. The design is based

on a specified impulse test level of 1 250 kV. A companion paper by Rippon* contains full particulars of the new transformers and of the large variety of voltages that can be obtained with the least possible reactance by the various combinations of the old and new transformers.

### (4.7) Power Cables

Most of the cables used to connect the generators to the making switches and power transformers are 3-phase cables of the belted type, having a copper section of $0 \cdot 5\,\text{in}^2$. Two such cables are run in parallel for each generator. The adoption of 3-phase cables wherever possible has enabled their reactance to be kept down and reduced the problem of cable movement due to electromagnetic forces. Overheating of the cables presents no problem because of the short duration of the test currents. However, attention had to be given to the forces between conductors tending to burst the cable; this force was calculated to limit the capacity of each cable to 53 kA (r.m.s.), i.e. over 100 kA for the two cables in parallel.

For some connections to the power transformers $1\,\text{in}^2$ single-core paper-insulated lead-covered cables are used. To eliminate the possibility of sparking at the cable sheath, owing to the induced voltage when large currents pass through the core, it was decided to earth the sheath at both ends. To avoid overheating of the sheath as a result of the large currents induced in it, a $0 \cdot 5\,\text{in}^2$ copper conductor is run in parallel with it. With this arrangement it is possible to pass a fault current of 60 kA through the cable for 0·5 sec without risk of damage to the sheath.

The bracing of the single-core cables presented some difficulty owing to the possibility of large attraction or repulsion forces between them. Where the cables are supported in racks it is found necessary to brace them continuously along their whole length by suitable wood blocks. Where they are laid underground they are rigidly clamped at short intervals in a concrete trench which is filled with sand and covered by reinforced concrete.

### (4.8) Other Main Equipment

Some of the other items of main equipment installed at the new station are as follows:

(*a*) A low-voltage power transformer for short-time heavy-current tests.

(*b*) Capacitors for the control of rate of rise of restriking voltage and for switching tests with limited capacitance. These capacitors consist of 24 units each with a capacitance of $0 \cdot 05\,\mu$F and suitable for a working voltage of 150 kV d.c. or 57 kV a.c. (r.m.s.). Some of them are mounted on insulated supports so that they can be connected in cascade for tests up to the highest voltages of the station.

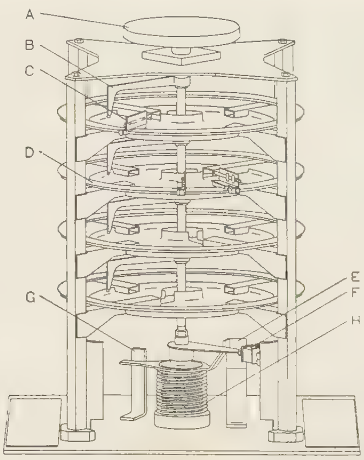
(*c*) A compressed-air installation, including oil-cooled compressors capable of providing a maximum pressure of $1\,000\,\text{lb/in}^2$.

## (5) MEASURING AND CONTROL EQUIPMENT

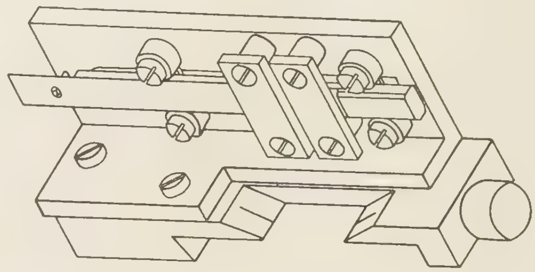
The measuring and control equipment is housed in the observation building, which also contains observation rooms, offices, dark rooms, etc. Much of the equipment is conventional and has been described in previous publications. Three items, however, deserve special mention.

### (5.1) Time-Sequence Controller

After the merits of the pendulum and the various drum-type controllers had been considered, it was decided to design a special controller having the accuracy and long scale of the pendulum and the ability of the drum-type controller to actuate a large number of contacts.




(*a*)



(*b*)

**Fig. 7.**—Time-sequence controller.

(*a*) General view.
A Flywheel.
B Contact operating arm.
C Contact.
D Graduated circular scale.
E Brake.
F Releasing latch.
G Stop.
H Spring.

(*b*) Enlarged view of contact C.

The controller thus developed is illustrated in Fig. 7. The moving system is given an impulse by means of a pre-charged spring, which is released electrically; it then rotates through 300° by virtue of the inertia of the flywheel which forms part of it, losing only about 3% of its speed during its travel.

Four arms projecting at different levels sweep across four graduated circular scales on each of which are mounted a number of contacts. These can be moved so that they are actuated by the arms at predetermined time intervals, and in this way it is possible to obtain as many as 28 independent contact operations with a great degree of accuracy.

### (5.2) Panel for Checking of Main Circuit Connections

It is obvious that with 3-phase or single-phase circuit connections adjustable to give voltages corresponding to rated (3-phase) voltages up to 380 kV, there is a multiplicity of main circuit connections, and an error in any one of these may have serious consequences. Equipment has therefore been installed which effectively checks the connections before the short-circuit is applied. Two devices are used: one indicates the output current of the generators, and so safeguards the generators, the test-piece, and the associated connections; and the other checks the current in the individual power transformers, and so safe-

* Rippon, E. C.: "Design and Constructional Features of a 275-kV Special-Duty Transformer Bank," *Proceedings I.E.E.*, 1954, **101**, Part II, p. 431.

guards them and their connections. The operation of both devices is based on currents flowing during a preliminary short-circuit, which is applied at a reduced voltage; the indications thus obtained are a measure of the currents that will flow during the subsequent full-scale short-circuit.

The first device is a moving-coil instrument in which the permanent magnet is replaced by an electromagnet with a core of high remanence. This is energized for a predetermined short time by rectified current derived from the output of the generators. A small direct current is then passed through the moving coil and the pointer indicates the magnitude of the remanent flux and hence of the generator current. The scale of the instrument is calibrated in amperes.

The second device comprises a set of instantaneous over-current relays, each associated with a power transformer. Each relay is set to remain non-operative at the current that, with correct connections, flows in the associated power transformer during the preliminary short-circuit at reduced voltage. Operation of any of the relays therefore indicates that it is unsafe to apply the full-scale short-circuit.

### (5.3) High-Speed Cathode-Ray Oscillograph

The oscillograph has four sealed 10-kV cathode-ray tubes which are focused by four separate lenses on to a film mounted on the external rim of a rotatable camera drum. By adjusting the position of the lenses all four traces can be brought approximately to the centre of the film width. The standard motor drive gives film speeds up to 50 m/s, and higher speeds can be obtained by means of a special drive. Writing speeds of at least 500 000 m/s can be obtained, and this permits satisfactory recording of frequencies of more than 1 Mc/s.

## (6) CONCLUDING REMARKS

The authors believe that the testing station described in the paper is likely to play an important part in the future development of circuit-breakers. The high output which it provides up to the highest voltages opens up many opportunities for research on circuit-breakers and for their development and design, unfettered by limitations of testing-station output which have been a brake on progress hitherto.

## (7) ACKNOWLEDGMENTS

The authors wish to record their thanks to the Directors of A. Reyrolle and Company, Limited, for permission to publish the paper and for facilities placed at their disposal; to Messrs. F. C. Winfield and T. W. Wilcox of Merz and McLellan for advice in the early stages of planning of the testing station; and to Mr. J. F. Bird, who has played a leading part, and many other colleagues for their valuable assistance throughout all stages of the work.

## DISCUSSION BEFORE THE SUPPLY SECTION, 23RD MARCH, 1955

**Mr. L. Gosland:** The papers contain some fifty Sections and Sub-sections, most of them worthy of comment. Discussion must concern a few major points, and fortunately the necessary selection is indicated by Section 7 of the paper by Messrs. Christie, Leyburn and Bird, in which the authors set out those details of testing procedure which require fresh consideration. The first three items seem unexceptionable, but Section 7.4 raises important issues. The recommendations concerning the asymmetrical test agree generally with the practice followed in the E.R.A. ever since Dr. Whitney first started circuit-breaker tests in 1923, and, by his early perception of the importance of almost every detail now under discussion, set a pattern almost universally followed. I am sure that the authors are only recommending a course which they themselves have taken in every development test made on their plant. A clause to cover the suggestion that the arcing period in asymmetrical tests must be the same as in the normal symmetrical test would, however, require rather careful drafting. It is mentioned that system power factors are not really as low as $0 \cdot 075$. If this is so, do we need peak asymmetrical currents as high as $1 \cdot 8I$ to cater for the sub-transient reactance?

Few would contest the suggested increase in the minimum recovery voltage permissible for tests at reduced voltage. These tests are only acceptable where nothing better is possible, and the more closely they approach service conditions the better. The arguments on the subject in the paper hinging on the arc-voltage magnitude suffer from compression. Many other factors enter into the matter.

Standardization of r.r.r.v. has been long discussed and does not offer difficulty if the system conditions envisaged are properly set out; but decision on this matter should in principle await that on the next point raised, namely the recovery voltage for single-phase tests. The authors argue that, although undoubtedly the first phase to clear in a 3-phase unearthed fault is subject to a momentary peak voltage of $1 \cdot 5$ times the normal, this fault condition at full rating is highly improbable, and since the construction of a circuit-breaker to meet the condition adds to the expense, a lower figure should be adopted. This seems to be a case where an appeal should be made to experience, as illustrated by fault records, and the potential savings should be weighed against the potential cost of an improbable failure.

The value of $1 \cdot 5$ is not the highest which can be put forward. In the early 1930's Dr. Bruce studied the relative severity of single-phase and 3-phase tests and was led to consider all types of fault. He concluded that in a 2-phase-to-earth fault with high zero-sequence impedance, the first phase to clear had a recovery voltage of $1 \cdot 7V$. A supporting analysis of reported circuit-breaker failures showed that there were far more failures in 2-phase-to-earth faults than would be expected from their relative frequency of occurrence. There was considerable discussion at the time, but so far as I know, no circuit-breakers have ever been tested on single phase at $1 \cdot 7V$. There may have been one or two failures in consequence, but there is no alarm, and it is possible that $1 \cdot 5$, which is a theoretically determined value, may be as unnecessary as the value $1 \cdot 7$ seems to be.

The authors suggest that single-phase tests may be slightly less onerous than 3-phase ones because of the absence in the former of an increase in the length of the current loop in one, and a shortening in the other, of the second two phases to clear. Dr. Bruce elaborated at the same time the contrary point. Interruption of an arc must involve some element of chance, and since in a 3-phase test there are three chances per loop for extinction of a first phase, while in a single-phase test there is only one, the latter will tend to give longer arc durations and thus be slightly more severe.

The request for wider tolerances of the magnitudes of intermediate currents seems reasonable when considered in relation to Fig. 5 of the paper by Messrs. Christie, Leyburn and Fenn, which shows at some points a considerable gain in r.r.r.v. by a small reduction in the current, thus permitting the use of fewer transformers. The remaining four points in Section 7 of the paper by Messrs. Christie, Leyburn and Bird seems unexceptionable, although they seriously extend standard proving schedules. The view taken of synthetic testing is understandable

but disappointing. These things do seem to take a long time. The much simpler related problem of measuring arc currents near the current zero has been vigorously attacked for ten years by many organizations, and only recently have satisfactory solutions begun to emerge. The problem of synthetic testing will probably eventually be solved to the extent of providing a satisfactory compromise, at least for development. At the E.R.A. we use synthetic or substitute testing a good deal, but we are not trying to prove circuit-breakers.

The amount of material in the paper devoted to the technique of testing may distract attention from the important engineering details of the paper on the proving station. The use of the U-connection for matching the voltage of the over-excited generator to the transformer winding ratios is ingenious. With that arrangement can over-excitation be used to maintain a standard recovery voltage against decrement, or is 22 kV the maximum possible voltage? The making switch is also interesting, and accuracy to within ±10° seems sufficient for proving tests and general development. The plant, however, is also used for research investigations, and for such, this is a very large variation. Possibly the performance is better when these switches are used separately in tests below the maximum output.

The authors use the testing station a great deal for research as well as for the testing now under discussion, and doubtless they have an array of research equipment and techniques to suit the scale of the station. It may be hoped that they will find the time and opportunity to describe these in a later paper.

**Monsieur Y. Baron** (*France*): With regard to Section 2 of the paper by Messrs. Christie, Leyburn and Bird, I suggest that circuit-breakers should be classified in accordance with the way in which the arc-extinguishing medium is put in operation. First we have impulse circuit-breakers, the impulse being given from a mechanical device and not from the energy of the arc (air-blast and impulse oil circuit-breakers). Secondly we have circuit-breakers using the energy of the arc, without any external means (tank-oil or small-oil-volume circuit-breakers, so long as they do not include a mechanical device giving an oil impulse). Thirdly we have circuit-breakers using simultaneously the two above-mentioned means (tank-oil, small-oil-volume and air-break circuit-breakers).

I agree with the authors that there is a need for standardization of r.r.r.v.'s and amplitude factors based on realistic system conditions. In the last edition of the French specification U.T.E.C64–100 for h.v. circuit-breakers, a Table details a set of values of the natural frequency corresponding to 50%, 75% and 100% of the rated breaking capacity. For easier comparison with Table 1 of the paper, the natural frequencies have been translated into r.r.r.v., assuming the rated minimum value of the amplitude factor with respect to the percentage of the rated breaking capacities (see Table A). These values roughly correspond to the actual r.r.r.v. of natural frequencies encountered in actual service conditions in French distribution, sub-transmission and transmission networks. The comparison shows that the figures given in the French specification have, within the range 66–275 kV, lower values than the British ones for 100% of the rated breaking capacity.

Table A

| Service voltage | R.R.R.V. at the given percentage of rated breaking capacities | | |
|---|---|---|---|
| | 50% | 75% | 100% |
| kV | V/μs | V/μs | V/μs |
| 7 | 1 240 | 580 | 293 |
| 17·5 | 1 360 | 612 | 305 |
| 25 | 1 450 | 655 | 310 |
| 35 | 1 570 | 700 | 325 |
| 70 | 1 980 | 890 | 370 |
| 100 | 2 320 | 945 | 405 |
| 170 | 3 100 | 1 300 | 495 |
| 250 | 4 000 | 1 640 | 595 |

In Section 4.1 the authors are in favour of a possible reduction, for e.h.v. circuit-breakers, of the recovery voltage at the 100% duty, which must at present be 1·5 times the maximum phase-to-earth voltage, according to I.E.C. specification No. 56, B.S. 116, and the French specification U.T.E.C64–100. If consideration is given to out-of-synchronism conditions (Section 4.10), the circuit-breaker under test has to break a current equal to 25% of the rated symmetrical short-circuit current with a recovery voltage of at least twice the maximum phase-to-earth voltage. On the other hand, care must be taken of the possible occurrence, after the clearance of a short-circuit or the tripping of a bulk of load, of a dynamic over-voltage owing to the inertia of governors and voltage regulators. The voltage may then rise temporarily above the maximum rated values, and there, if a circuit-breaker has to operate during that time, a higher recovery voltage will appear across its terminals. This has been confirmed by preliminary investigations in France. Thus if there is an international tendency towards lower figures for the recovery voltage than 1·5 times the maximum phase-to-earth voltage across a single pole during single-phase tests, a safety margin must, in any case, remain in order to take care of realistic operating conditions.

It is well known* that a developing fault generally begins with a small current to be broken, which happens to turn into a larger short-circuit current through a flashover or a breakdown occurring in the network. This may happen when switching off lines or transformers on no load. As developing faults appear during the arcing time of the circuit-breaker, the restrike may develop high shock pressures, thus endangering the interrupting chambers. I think that tests on this special point are necessary and are a complement of line-dropping tests, because, although from a statistical point of view they seldom occur, when they do occur they are likely to bring about a difficult situation.

**Mr. G. F. Peirson:** If the authors had been seconded to a switchgear testing company and been asked to produce a station having similar capabilities, would they still have adopted the U-connection and over-excitation? I can certainly vouch for the neat appearance which the back entry to the testing cells gives, and this neatness lends an air of efficiency which, while it undoubtedly exists, cannot fail to impress those who witness tests.

In the paper by Messrs. Christie, Leyburn and Bird, the authors rightly state that testing should prove circuit-breakers capable of dealing with both short-circuit and normal service conditions. In Section 4.11 they suggest an additional proving test at 5% of the short-circuit rating; this is important and well worth pursuing. I believe that the I.E.C. specification requires a duty test to be carried out at 0·5% of the short-circuit rating of the circuit-breaker, which is presumably in order to determine the performance of the circuit-breaker under the conditions visualized by the authors. It seems that, in order to prove the performance of a circuit-breaker for service for controlling, say, a transformer feeder, the introduction of tests at values even lower than 5% may well be necessary. Such tests would establish whether or not the arc energy at these low currents was sufficient to produce the required pressure within the arc-control device in order to scavenge that device and re-establish the electric strength sufficiently to prevent restriking.

The points made by the authors on the interruption of reactive fault currents at values between 10% of the short-circuit rating of the circuit-breaker and the highest transformer magnetizing

* C.I.G.R.É., Paris, 1954, Paper No. 149.

current are somewhat confusing. The selection of the appropriate MVA rating of a circuit-breaker is determined by the point on the system at which it is to be installed, and almost invariably it will have an inherent current-carrying capacity vastly in excess of that required for any transformer which it may be required to switch on or off. I was uncertain, therefore, about the effect that such a circuit-breaker would have and how it would be proved by merely adhering to the 5% test to which the authors refer.

In Section 4.8 the authors deal with auto-reclosing duties. To what extent might the breaking capacity of circuit-breakers be reduced if the duty were increased from the 2-unit test of break and make-break specified in the paper to a 4-unit test of break, make-break, make-break, make-break?

In Section 4.10 the authors come to the conclusion that, so far as asynchronous conditions are concerned, the most severe duty would be met by testing at 25% of the rated short-circuit current at $2V/\sqrt{3}$. Have the authors arrived at this conclusion on the basis that two simultaneous earth faults are uncommon and that h.v. systems are generally solidly earthed? If so, the figure may be a little low, if we consider a circuit-breaker for use on a Petersen-coil earthed system.

**Mr. C. H. Flurscheim:** The primary limit of breaking capacity of air-blast circuit-breakers is determined by the race between build-up of electric strength and electric stress at current zero. As air-blast circuit-breakers are susceptible to both r.r.r.v. and 50 c/s recovery voltage, tests at reduced recovery voltage can be increased in severity by increasing the r.r.r.v. above the rated level of the circuit-breaker. The degree of compensation necessary can be determined from a broad testing background.

In the case of oil circuit-breakers, the principal limitations in breaking capacity are not only those associated with the dielectric condition in the arc gap, but also arise from the risk of electrical breakdown in the gases inside and outside the arc control devices immediately after interruption, from the risk of secondary explosion, and from shock to the structure. These limits cannot be simulated effectively unless full voltage is associated with full current, and reduced voltage cannot be compensated by increased r.r.r.v., since oil circuit-breakers are not sensitive to this circuit characteristic.

I therefore conclude that reduced voltage tests can be considered more justifiable on air-blast circuit-breakers than on any form of oil circuit-breaker, which is contrary to the view expressed by the authors. Nevertheless, in the present state of the art, full-voltage testing of interrupter components at full current should be accepted as standard for all types. I agree that the voltage to be considered is the appropriate fraction of $1 \cdot 2E_n$ associated with one interrupter, which is a realistic assessment of service conditions at maximum fault power on solidly earthed neutral networks.

As regards the 50 c/s voltages appearing across one pole at lower currents, this progressively rises until, at 25% power, 2 or $2 \cdot 5$ times the phase-to-neutral voltage can occur, although even higher voltages in excess of $3 \cdot 5V_n$ can be associated with small currents on Petersen-coil networks.

I agree, in general, with the realistic curves for r.r.r.v., given by Messrs. Christie, Leyburn and Bird in Fig. 5 of their paper, for rigid networks. However, I consider the standardized rates should be associated with microvolt-amperes, and for fault values of 15 000 or 25 000 MVA, lower rates will exist on networks, since the fault contribution fed through transmission lines will be higher. Therefore, I think that a rate of the order of 750 volts/microsec should be specified at 15 000 MVA.

On actual networks, relatively low over-voltages and high rates are associated, as are relatively high over-voltages with low rates. It seems, therefore, that two standards should be established; for rigid networks a maximum over-voltage of $2V_n$ and the rates generally as given for Fig. 5; for weak networks, $2 \cdot 5V_n$ 50 c/s over-voltage associated with a lower level of rate of the order of 2 kV/microsec at low currents and 400 volts/microsec at 100% rating. It would not prove economical to associate extreme voltages and extreme rates in the same design, nor is this a network requirement.

**Mr. D. M. Cherry:** I will confine my remarks to Section 4.1 of the paper by Messrs. Christie, Leyburn and Bird. It seems that the authors are amongst those who hold that it is gross heresy for any test of a circuit-breaker to be conducted in a condition which is not demonstrably liable to occur in practice. They point out, however, that with oil circuit-breakers the main problem is mechanical. In mechanical circles the practice of carrying out a test at something more than the service conditions is very well established; so that certainly where oil circuit-breakers of the self-generating type are concerned, I remain a heretic, and like M. Baron, particularly so on the subject of single-phase testing at $1 \cdot 5$ times the recovery voltage.

The authors are correct, or nearly so, when they say that this condition cannot occur on a solidly-earthed system. However, there are many other considerations which have to be taken into account, particularly with oil circuit-breakers of the self-generating type which attempt to break voltages of 50 kV or more on a single break. Mr. Flurscheim has pointed out that the performance is by no means so easily extrapolated from tests at less than full scale as was once thought. For instance, the arc can easily operate for another half-cycle and introduce very severe stresses. When, by convention, three shots at a given setting are held to be sufficient to establish the performance, there is a question of whether that is sufficient when we have only an occasional extra half-cycle of arcing. This particularly applies with single-phase testing, where on one duty cycle only three possible happenings are examined, as against nine in 3-phase testing. It would be imprudent for these reasons to reduce the factor of $1 \cdot 5$ simply because there is some doubt about whether it can occur with any worth-while frequency in practice.

Another question is that of the sustained recovery voltage which occurs in single-phase testing, whereas, of course, with 3-phase testing the high voltage ($\times 1 \cdot 5$) is only momentary on recovery. This is, of course, quite unfair; there is no possibility whatever of that type of thing occurring in practice in normal networks. The advantage of the sustained voltage, however, is that with large oil circuit-breakers it has the effect occasionally of inducing a re-ignition. There is nothing inherently objectionable in the re-ignition of the arc for a single half-cycle after it is first interrupted, provided, of course, that it all takes place in the interrupter. The successful clearance of a re-ignition gives a valuable proof of the mechanical strength of the interrupter to withstand an additional half-cycle of arcing, or the effects of developing faults such as M. Baron mentioned.

It has to be remembered that these interrupters are very indeterminate structures, of very indeterminate materials, subjected to impulsive pressures of the order of 1 000 lb/in$^2$.

I therefore feel that no real injustice is done by single-phase testing at $1 \cdot 5$ times the nominal recovery voltage—at least in the present state of development of oil circuit-breakers. The position may be slightly different for air-blast and impulse-type circuit-breakers.

The authors mention that there is a good deal of Continental and American support for reducing the factor of $1 \cdot 5$. In those circumstances I find it difficult to believe that the I.E.C. should have adopted, with as little argument as they appear to have done, this offending factor in the recent issue of I.E.C. Publication No. 56.

There is a good deal of resemblance between an oil circuit-

breaker in particular and a pressure vessel in the event of a failure. We have gratifyingly few failures of either device, and it is in general more difficult to design and prove a circuit-breaker than a pressure vessel. So far as these two papers and the authors' augmented test plant will serve to make this proving more definite, we should all welcome them.

**Mr. J. S. Cliff:** I do not think that the remarks in the paper by Messrs. Christie, Leyburn and Fenn on super-excitation do justice to the undoubted benefits which can be obtained from it, particularly for high-voltage single-phase testing. Over 20 years ago I put into operation the first testing station in this country to use super-excitation.* As was clearly shown, when super-excitation is correctly applied there is no undulating curve as given in Fig. 3. It was also shown that at approximately 750 MVA 3-phase super-excitation gave a gain of 87% in MVA output and 37% in recovery voltage after a short-circuit duration of 7 cycles. Similar gains are achieved at higher single-phase powers, such as are obtained when using the high-voltage transformers.

To achieve satisfactory results the generator must be operated with the iron saturated. With our machines the voltage only increases by 30% from 11 to 14·5 kV if the field current is increased seven times. The authors' machines appear to be much less saturated and unsuitable for satisfactory super-excitation.

The authors' explanation of the advantages of the U-connection seem to be fallacious. With the normal connection we obtain $22^2/4x = 120/x$ MVA. With the U-connection we get $19\cdot1^2/3x = 120/x$ MVA, i.e. exactly the same output, as would be expected from merely reconnecting the windings. The authors increase the voltage by 15% and get $22^2/3x = 160/x$ MVA, or 32·5% more. This is merely because MVA output is proportional to the square of the voltage, and $1\cdot15^2 = 1\cdot325$. With our machines we can get exactly the same increase using the normal connection by increasing the voltage of 22 kV by 15%, giving $25\cdot4^2/4x = 160/x$ MVA. We can also do much better than this by applying super-excitation 40 cycles before the short-circuit to obtain 14·5 kV on a normal 11 kV connection, thus obtaining $14\cdot5^2/x = 210/x$ MVA, i.e. an increase of 75%. The reduction in machine reactance due to the U-connection is insignificant, and a similar reduction is obtained by using super-excitation and the normal connection. The authors' three machines give an output of 4 700 MVA; our two machines with super-excitation will give an output of 5 600 MVA. The machine end-windings are adequately braced to withstand these powers, and parallel operation presents no difficulties up to full power and super-excitation, since using our arrangement one engineer controls two generators and two exciters from a single field control, and the super-excitation is applied automatically by closing a single contactor. In my opinion to design modern short-circuit testing generators without super-excitation is wasting both output and money.

Increasing the voltage on the normal connection has the advantage that it gives a higher applied voltage than the rated voltage of the circuit-breakers, so that the recovery voltage will be nearer to 100% after some decrement, than with the authors' U-connection. Although we have all the facilities for using the U-connection we prefer to operate our machines and transformer primary windings at 11 kV, and thus avoid the complication of a making switch similar to that of the authors. Our making switch is simply air insulated with three mechanically coupled phases which can be operated in parallel for single-phase testing. For the last 15 years this switch has been operating with point-on-wave closing to ±10 electrical degrees without any difficulty, thus enabling us to select symmetrical or asymmetrical single-phase currents, and so to reduce the short-circuit duration and use the plant at its maximum capacity.

* Cliff, J. S.: "Apparatus used for High-Power Switchgear Testing," *Journal I.E.E.*, 1937, **80**, p. 593.

**Mr. C. W. Mott:** My remarks are confined to the paper by Messrs. Christie, Leyburn and Bird. For several years the proving of high-power circuit-breakers has been the subject of agreement between manufacturers, testing authorities and users. Many of the tests proposed in the paper, together with others not mentioned, have been applied to modern circuit-breakers for use in this country.

Tests for proving a circuit-breaker will depend on its type, form of construction, operating characteristics, and the output available from a given test plant. It is unlikely, therefore, that a single schedule of tests will give adequate proving of all circuit-breakers of a given rating irrespective of type, neither is it probable that such a schedule will give adequate proving of circuit-breakers of the same type on different test plants. It would appear, therefore, that the proving of high-power circuit-breakers will continue to be the subject of agreement between interested parties.

The authors pay particular attention to high-power e.h.v. circuit-breakers, but Fig. 2 gives arc-length/voltage characteristics for maxima of 9 kA and 15 kV. For 9 kA the arc length is shown to be almost constant over the range 7–13 kV, and from this it is concluded that the arc length and pressure in an oil circuit-breaker are not greatly affected by reduction in test voltage.

These curves would be of greater value if plotted over the range, say, 20–50 kV, at 15 kA, when I suggest that different characteristics might be revealed. I have known oil-circuit-breaker interrupters to operate very satisfactorily at 15·3 kA, 40 kV, but fail with disastrous results at 15·3 kA, 50 kV. The higher voltage can bring about an additional half-cycle or more of arcing, which results in a considerable increase in the arc energy liberated in the interrupter.

The r.r.r.v.'s given in Fig. 5 are of considerable interest. For the last five years manufacturers have been pressed for values between 7 and 10 kV/microsec at 10% and 30% of the rated breaking current for 132 and 275 kV circuit-breakers. We now appear to have reached agreement at this end of the curves. The right-hand end of the curves shows that the r.r.r.v. at 100% rated breaking current is practically constant, irrespective of the service voltage. Again, manufacturers have been asked for a constant r.r.r.v. at this current for 66, 132 and 275 kV circuit-breakers over the same period, and we now appear to have reached agreement as to the value being constant. We have yet to reach agreement on the actual value, and it is prudent at this stage to consider figures put forward by other authors.

From Fig. A we see that in a paper presented to The Institution in 1949, the maximum r.r.r.v. for a 3 500 MVA 132 kV system is given as 700 volts/microsec at 100% rating. In a paper before C.I.G.R.É. in 1954, this has increased to approximately 2 100 volts/microsec, and the authors at present propose a figure of about 1 600 volts/microsec. It is pertinent to ask the reason for the increase since 1949, and I suggest that it is due to the larger plant units now being used and the growth of the system. No one would be bold enough to suggest that we are using the largest plant units possible and/or that the system will not continue to grow. Hence, further increases in these values are expected in the future.

Circuit-breakers purchased at the present time are expected to have a service life of at least 20 years, and they should be suitable for service conditions likely to be experienced during that period. Moreover, the figures quoted are test values to be applied when testing circuit-breakers by complicated testing procedure usually necessitated by the limited output available from a given test

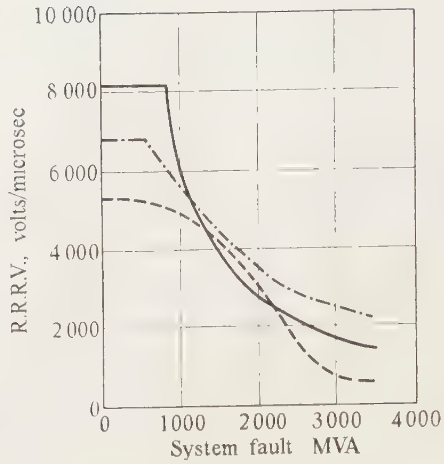



**Fig. A.**—Estimated limit of r.r.r.v. for 3 500 MVA 132 kV system.

——— Obtained from the paper by Messrs. Christie, Leyburn and Bird.
—·—·— Obtained from a paper read before the C.I.G.R.E. in 1954.
– – – – Obtained from a paper by Flurscheim and L'Estrange.*

* Flurscheim, C. H., and L'Estrange, E. L.: "Factors Influencing the Design of High-Voltage Air-Blast Circuit Breakers," *Proceedings I.E.E.*, Paper No. 775 S, November, 1948 (96, Part II, p. 557).

plant. In the circumstances I consider that the figures put forward by the authors for proving circuit-breakers are too low, and I do not agree that the values specified by one user in this country are excessive.

**Mr. L. C. Walshe:** I am pleased to see the proposed introduction of a test at 5% breaking duty, which I have always considered to be extremely desirable with oil circuit-breakers, particularly when the arc length at 10% duty exceeds that at 30%, and also when the arc projects beyond the arc control device.

There seems to be some confusion as to the intention in the proposed reduction of recovery voltage to $1{\cdot}0$ or $1{\cdot}3V\sqrt{3}$ in Section 4.1 of the paper by Messrs. Christie, Leyburn and Bird. This is associated with the question of rise of voltage under asynchronous conditions after a system has divided. In this country it is most unlikely that the final separation between two sections of the Grid system will take place on an actual fault; sequential tripping is far more likely, with final separation at a comparatively low current. This does not apply on many oversea systems, where there is considerable power transmission with the generating source concentrated many hundreds of miles from the load centre. Under these conditions a much more serious voltage condition can arise, and the increase to $2{\cdot}1\,V\sqrt{3}$ suggested in Section 4.10 is desirable.

The authors dismiss the question of synthetic testing as being of little future importance. They base their decision on the opinion that such tests can contribute little to tests on separate units and show no economies in test-plant design. It is important to note that at no stage in the testing of most multi-unit circuit-breakers is the maximum voltage present at the same time as maximum current. There is no check on the possibility of breakdown between the contacts and the tank through the contaminated oil, and bubbles emitted from the arc control device in an oil circuit-breaker or on flashover through an ionized gas cloud outside an air-blast circuit-breaker. Have the authors seriously considered this question, and what are their views on the use of a synchronized auxiliary source to apply a voltage between the contact under test and the normally earthed metal during heavy-duty testing? This would mean fully insulating either the test transformer or the normally earthed metalwork on the circuit-breaker. In the authors' opinion, is this risk so small that it may be completely ignored?

**Mr. J. M. Hawkins:** I agree with the authors that it is unlikely that circuit-breakers will be subjected to the duty of interrupting highly asymmetrical currents in service. This is particularly so in e.h.v. networks, where a fault is bound to be initiated by a flashover which will occur at a comparatively high voltage, i.e. near the peak of the sinusoidal supply voltage, and therefore leads to a symmetrical or approximate symmetrical fault current. This will apply also to ultra-high-speed circuit-breakers and to circuit-breakers opening on a developing fault. I cannot therefore agree with the authors that these cases are exceptions to the rule.

In my experience the curve shown in Fig. 3 of the paper by Messrs. Christie, Leyburn and Bird is far steeper than it should be. I should be interested to know how the authors measured the r.r.r.v. in their experiments. When the method referred to in Section 3.2.3 is used, a reduced voltage having supposedly the same r.r.r.v. can stress the circuit-breaker more severely in the earlier stages of recovery, as will be seen by superimposing two restriking voltage transients of differing voltage, but of the same r.r.r.v. (by definition) upon a typical circuit-breaker recovery characteristic. Under these conditions the slope of the characteristic in Fig. 3 might well be in the opposite direction (see Fig. B).

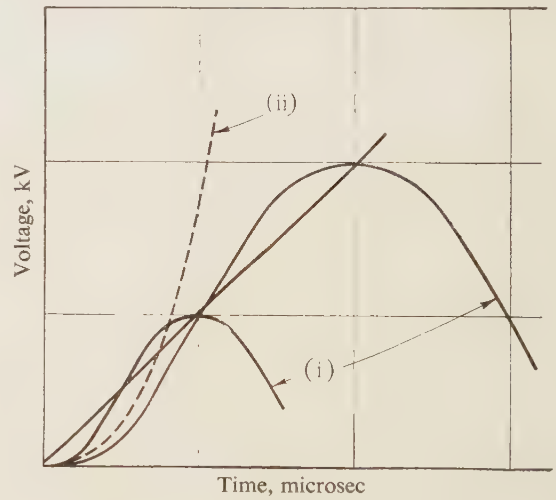



**Fig. B**

(i) Restriking voltages of differing amplitude but the same r.r.r.v.
(ii) Circuit-breaker recovery characteristic.

In Section 3.2.3 the authors stress the need for standardization of restriking voltage on the basis of realistic system conditions, and I wholeheartedly agree. It should be emphasized, however, that the figures they have put forward represent severe conditions, and it may well be desirable, in the interest of economy, to have, in addition, a lower standard which would cover the conditions to be encountered at perhaps 80% of the switching locations in the electrical networks of the world.

There are now a number of short-circuit testing laboratories in this country of a size similar to the one described in the paper, but there are no comparable facilities for the testing of circuit-breakers for the duty of line switching. I have had the good fortune to be able to witness and study in detail tests made on the e.h.v. network of Électricité de France at Fontenay, and of taking part in the first line-switching tests on the 275 kV system in this country. In both cases valuable results have been obtained. I would therefore make a plea that testing facilities should be established on the networks of this country that could be made available both for the proving and development of circuit-breakers for this important duty.

The comparison made by the authors between super-excitation

and over-excitation of short-circuit alternators is somewhat misleading, since the example of super-excitation is in no way representative of a well-designed system. One of the advantages of super-excitation is that a comparatively flat current/time characteristic is obtained simulating a fault current in a large network, and enabling a well-controlled test to be made. Over-excitation, on the other hand, must lead to a more rapidly falling current during the period of the test.

Although I am deeply involved in it myself, I think that short-circuit testing is somewhat glamorous and its importance can easily be over-emphasized. It is salutary to remind ourselves that most of the faults on circuit-breakers in service are not connected with the interruption of short-circuit currents, but are due to mechanical and insulation defects, or to the influence of ambient conditions.

**Mr. W. Casson:** In Section 4.9 of the paper by Messrs. Christie, Leyburn and Bird, it is stated that "Although, in certain system conditions of earthing, the single-phase fault current can exceed the balanced 3-phase fault current, this condition is not common and no special account need normally be taken of this." It is well known that when the ratio of $X_0$ to $X_+$ is unity, where $X_0$ is the zero-sequence reactance and $X_+$ is the positive-sequence reactance, the magnitude of the line currents for 3-phase faults, 2-phase-to-earth faults, and single-phase earth faults is the same; and where the ratio is zero, in the theoretical limit, the line current in the 2-phase-to-earth fault is $1 \cdot 73$ times that in the 3-phase fault, and $1 \cdot 5$ times that in the single-phase fault. The authors do not seem to be aware of the fact that on the Grid system the ratio of $X_0$ to $X_+$ at some of the important switching stations in the future, where there are large concentrations of 275/132 kV transformers, Area Board supply transformers and generator transformers, may be as low as $0 \cdot 3$, which means that line currents on earth faults will be in excess of those on 3-phase faults by some 30%.

It would appear, therefore, that, although for circuit-breakers on systems earthed at one or a few points no special account need normally be taken of this condition, it does not apply to circuit-breakers for use on such systems as the Grid in which the transformer neutrals are solidly earthed. Do the authors consider that proving tests on such circuit-breakers should include a single-phase-to-earth fault test in which the current would be some 20–30% in excess of the 3-phase rating current, and also do they consider that there would be any great difficulty in designing circuit-breakers to meet these conditions—of course, at no extra cost?

[The authors' reply to the above discussion will be found on page 726.]

## NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 10TH JANUARY, 1955

**Mr. H. E. Cox:** As time passes and more experience is gained on test plants, designers, manufacturers and users are realizing that the breaking-capacity tests specified by the I.E.C. and B.S.I. are not sufficient to prove circuit-breakers as suitable for all conditions that they may be called upon to meet in service. The more experience that is gained the more conditions are brought to light, and testing and design engineers are faced with trying to devise tests that will cover all conditions and yet keep the amount of testing within the realms of reason. Indeed, the further this problem of devising a comprehensive test code is investigated the more hopeless it appears, and I think that the time is approaching when a new appraisal must be made.

In Section 7.2 of the paper by Messrs. Christie, Leyburn and Bird, it is stated that "All aspects of a circuit-breaker's performance must be proved and not a few specialized aspects." If this were taken literally it would mean that all variants of all circuit-breakers would have to be exhaustively tested as I cannot imagine any other way of "proving" than by test. Such a course would lead to a very severe brake on development and a by no means insignificant inflation of cost. I suggest that there may well be another way of solving this problem, and I should like to make my point by analogy, although, like most analogies, the parallel is not complete.

Constructional engineers have for decades designed structures which have been accepted by customers without extensive testing and which, nevertheless, have proved satisfactory in service. They have done this by using, not the most economical designs or the designs which use the least material, but by using designs whose performance can be predicted from certain component tests. The most economical structure is one with built-in joints and often with what are called "redundant members," but the most easily calculated structure is the pin-jointed structure.

Can the circuit-breaker designer, by relinquishing the quest for the minimum use of material, devise designs, the operation of which will be so certain that proving can be limited to tests on components (unit tests) augmented by a few simple tests on the completed circuit-breaker, the extra cost of material being more than offset by the saving in cost of testing?

It would appear that such circuit-breakers can be designed provided that certain limitations are accepted which I suggest might be as follows at the present stage of development:

(i) A single oil break should not exceed a 3-phase voltage rating of 66 kV and a 3-phase breaking-capacity rating of 2 500 MVA.

(ii) A single air-blast break should not exceed a 3-phase voltage rating of 33 kV and a 3-phase breaking-capacity rating of 1 000 MVA (this latter rating will vary with the r.r.r.v. for which the circuit-breaker is designed).

(iii) When circuit-breakers with greater ratings than those mentioned in (i) and (ii) are required, two or more breaks should be put in series.

(iv) When breaks are put in series, voltage division should be obtained by shunt impedance of sufficiently low value to ensure correct voltage division under all circumstances of breaking and making.

(v) During the switching operation the circuit should be damped so that excessive oscillating voltages cannot be formed on any circuit possible with any commercial arrangement of apparatus.

I do not suggest that single-break oil circuit-breakers cannot be made for voltages higher than 66 kV or 2 500 MVA rating, or that single-break air-blast circuit-breakers cannot be made for ratings higher than 33 kV 1 000 MVA. But if these ratings are exceeded the operation becomes less predictable, and therefore much more testing is required to prove that one rating or kind of operation has not been achieved at the expense of good operation on some other duty. Provided that these requirements are met it should be possible to carry out unit tests on single-break units and then to build up circuit-breakers of any breaking capacity and for any voltage by putting such unit breaks in series. Furthermore, provided that these limitations are accepted by the designer, unit tests for making and breaking capacity, line and condenser switching, and reactor switching, augmented by full voltage tests on one phase at 10% rating up to twice the leg voltage, should be acceptable.

It is interesting to speculate on the size of test plant that would be necessary to prove such designs. I think it can be accepted that 40 kA short-circuit current for high-voltage circuit-breakers will not be appreciably exceeded. Likewise, I feel that 500 kV will become the ceiling voltage.

Assuming these conclusions to be correct, the maximum size of test plant would be that which will give an output of 2 500 MVA

3-phase at 66 kV down to 36 kV and 4 kA at 580 kV (290 kV above and below earth).

With regard to the paper by Messrs. Christie, Leyburn and Fenn, the U-connection described is an ingenious way of obtaining maximum single-phase MVA output from a 3-phase generator. It does not, however, give more MVA output than the delta-connected generator, but it provides it at a different voltage. Whereas the U-connection gives the output at a single-phase voltage approximately equal to the star voltage of the 3-phase generator, the delta connection gives it at the phase voltage. Which is the better for a given testing station depends upon the turns ratio of the step-up transformers.

The outputs given by this new test plant are very impressive, but I wonder whether it will be expedient to achieve them in service. Under such excessive short-circuit currents most generators have a definite life, and it usually has to be decided how much output must be sacrificed for life and vice versa.

Provided that flashover on the generator connections can be eliminated, it is safe to rely upon the short-circuit limiting effect of the transformers as claimed under the penultimate paragraph of Section 3.4, but usually no such certainty exists and it becomes necessary to add a protective reactor in series with and close to the machine.

**Mr. J. Bennett:** I should like to make a brief reference to the short-circuit testing of circuit-breakers in the early 1930's and the effects upon circuit-breaker design. At that time few authentic data on the performance of circuit-breakers under short-circuit conditions were available. The earliest tests showed the need for considerable modifications to existing designs, such as the strengthening of the tank enclosure, improvement of contact assembly (in many cases the provision of arc-control devices) and more powerful closing mechanisms. First thoughts were that the cost of switchgear would increase. The improvements in the construction of the circuit-breakers and the additional information obtained from tests on their performance has, however, had the opposite effect, and higher MVA ratings were subsequently obtained from equivalent frame sizes. I feel safe in stating that the knowledge gained from the early testing stations has enabled switchgear costs for several ratings of equipment to be reduced by as much as 30% over a period of years.

The paper by Messrs. Christie, Leyburn and Bird reviews progress up to the present with particular reference to the higher voltages and powers now encountered. I note the authors' statement that additions are required to existing standard tests, and I would ask them, and the other engineers concerned including the user, not to agree on a specification of tests which will unnecessarily increase the cost of standard circuit-breakers. At present we find examples of circuit-breakers manufactured abroad and having ratings far in excess of present British standards, and I am sure that many of these circuit-breakers would not meet the requirements of our present A.S.T.A. tests. The authors record that the A.S.T.A. are already giving attention to the issues raised in the paper, and I hope that any revised standards will be based on international agreement.

**Mr. C. H. Morton** (*communicated*): Referring to the U-generator connections described in Section 3.5 of the paper by Messrs. Christie, Leyburn and Fenn, I do not think that the authors have made a true comparison of the U and normal connection, even allowing for the particular transformer ratios available.

From the information given in the paper I cannot see why over-excitation cannot also be applied with the normal connection, since, from Fig. 3, it appears that a recovery voltage of approximately 100% is obtained with an applied voltage of, say, 115% with over-excitation, and it therefore corresponds to the standard test voltage required.

Furthermore, the step-up transformers are not in circuit on a break test until the making switch is closed, and the subsequent rise of recovery voltage up to the point F in Fig. 3 would not appear to exceed the 5% over-voltage limit on the transformers referred to in Section 4.6.

Therefore, if over-excitation is assumed in both cases (or alternatively in neither) the MVA output of the generator by itself is exactly the same whichever connection is adopted. The current, however, would be greater with the U-connection for a short-circuit on the generator terminals, but with a step-up transformer interposed the current increase will be reduced (and may even become negative if the step-up transformer has a reactance greater than a critical value).

It would therefore be interesting to know whether, in fact, 15% over-excitation is possible with the normal 22 kV single-phase connection, and if so, how the current on the h.v. side would compare with that from the over-excited U-connection. Also, on making tests where the step-up transformers are in circuit before the application of the test current, how does the current in the first loop using the U-connection compare with that using the normal 22 kV connection over-excited, say, to the 5% limit of the step-up transformers?

With reference to Section 3.1 of the paper by Messrs. Christie, Leyburn and Bird, I would suggest that the term "normal (arcing) period for the particular duty" would be too indefinite to incorporate in any specification.

[The authors' reply to the above discussion will be found on page 726.]

## WESTERN CENTRE, AT CARDIFF, 7TH MARCH, 1955

**Mr. R. N. Buttrey:** Experience and measurements indicate that pressures on oil circuit-breaker pots may not be especially high at maximum currents. This is discussed at length in References 9 and 10 of the paper by Messrs. Christie, Leyburn and Bird. The modern oil circuit-breaker can be designed with controlled pressures. Different designs have their own specific problems and characteristics.

One use of resistors not mentioned is to tune at 10–20% of the maximum rating; such a resistor generally serves to cover requirements (*b*), (*c*) and (*d*) listed by the authors.

I do not agree that symmetrical currents are always straightforward in their effects. Mechanical defects, such as mechanism and contact stiction, very often show up only in 100% symmetrical breaks, so that I do not agree that these should be disposed with. Duty cycles of separate break and make-break tests might be considered, although certainly up to 44 kV I have never experienced any difficulty in making short-circuit currents without contact burning, so that any products of pre-arcing can be ignored.

Whilst I agree that the oil circuit-breaker seems to indicate generally an independence of voltage, it is well known that this is not completely so, and tests carried out under the old edition of B.S. 116 Part 2 are not always easily reproduced satisfactorily on an oil circit-breaker when tested at full voltage and current. This agrees with the authors' remarks on synthetic testing when they state that the test voltage must not be reduced to such an extent as to limit the arc voltage. Why do the authors limit the size of full-scale testing to 750 MVA? I suggest that, in view of the size of most modern test plants, 1 000 MVA would be a suitable limit. Probably, as the authors suggest, unit testing is

most satisfactory for higher ratings. A point which arises in connection with "fault-current releases" is the possibility of "blind spots" as a result of lock-out features which must operate when a circuit-breaker latches fully home, and consideration must be given to this matter for making duties with "fault current release."

Since most oil circuit-breakers extend their arc duration down to 10% of the rating, there would always appear to be a possibility of a critical current. It is presumed that the authors consider that testing down to 5% would cover such a possibility.

I agree that current, voltage and impulse testing of resistors is one of the essential stages in the design and building of an h.v. circuit-breaker.

**Mr. A. H. McQueen:** The authors illustrated the effect of r.r.r.v. on arc duration in oil and air-blast circuit-breakers. What is the comparison between bulk-oil and small-oil-volume circuit-breakers?

The effect of power factor on the rate of decay of the d.c. component is shown on some systems. Advantage can be taken of the higher power factor to reduce the severity of the test on circuit-breakers applicable to that system. Are there any simple means of determining the power factor at a particular point in the system, in order to aid in the selection of suitable circuit-breakers?

What is the difference between full-scale and unit testing, and how far is unit testing a true measure of full-scale testing?

The authors state that the new testing facilities will enable the designer to work with greater freedom and make it possible for better circuit-breakers to be produced. For what current and voltage rating circuit-breakers does this apply? Can we expect better circuit-breakers at 6·6 and 11 kV, and does it mean that the improved performance will increase the cost, or will the performance be achieved with greater simplicity and will there be a reduction in cost?

After a test certificate has been issued for a circuit-breaker, how much and what sort of modification can be tolerated before the circuit-breaker must be retested?

Test-plant conditions are stated to be more severe than those met with in service. Have the authors any experience of systems with the same degree of severity met with at the short-circuit testing station, and if not, why are tests made so severe?

**Mr. C. Morley New:** The papers demonstrate the thoroughness of circuit-breaker testing, which proves the reliability of circuit-breakers to undergo successfully the duties imposed on them. From the operator's point of view, therefore, it is important to know how many faults the circuit-breaker can clear with safety, without inspection or maintenance being carried out.

With bulk-oil 132 kV circuit-breakers the limiting factor is not the contacts so much as the formation of carbon in the oil. This carbon can, after a period, become deposited on the insulating surfaces, and if not removed it can cause an internal flashover. Owing to this limitation, particularly with the older circuit-breakers, it has been found advisable to pump out the oil and wash down the interiors of the circuit-breakers after the clearance of each fault. This aspect does not appear to be adequately covered by the standard tests.

**Mr. N. Care:** I have recently been interested in the use of automatic circuit reclosers on systems up to 11 kV, and there has been some discussion regarding the short-circuit test which should be applied to such equipment. These reclosers generally have a 4-unit operation to lock-out, as compared with the 2-unit break and make-break operation specified in the paper by Messrs. Christie, Leyburn and Bird. The open-circuit time, however, is generally greater than the 10–15 cycles mentioned by the authors, since it is felt that an open-circuit time of this duration would be insufficient to allow transient faults, caused by the presence of foreign bodies, to clear. The Americans recommended that reclosers having a 4-unit operation should be tested at 100% rating by applying 20 unit operations, and allowing a time interval of, say, 15 min at the end of each lock-out duty. The authors appear to recommend that the test duty should correspond to the service duty, i.e. that tests only be applied for a 2-unit operation. Whilst I realize that by no stretch of imagination can an automatic recloser be regarded as a circuit-breaker of large breaking capacity, it might be desirable to introduce 4-unit reclosing features on standard 11 kV circuit-breakers up to 250 MVA capacity. To what extent do the authors consider that the breaking capacity of a normal circuit-breaker would be reduced if a 4-cycle recloser duty were required, and what test duty would they recommend when testing circuit-breakers designed for such reclosing operations?

Some years ago I was concerned with field tests on 132 kV air-blast circuit-breakers in Birmingham. We were trying to assess the over-voltages likely to occur when breaking transformer magnetizing currents. I believe that the results showed that with abnormally high magnetizing currents, owing to current inrushes on the transformers, over-voltage transients occurred to a magnitude of about $3V$. With extended use of cable systems on the 132 kV network it is possible that greater use will be made of shunt reactors, and the conditions of switching will be more onerous. Have the authors any figures indicating the over-voltages which might occur when switching shunt reactors, and do they consider that any special design features should be incorporated for this type of duty?

With regard to Section 6.2 of the paper by Messrs. Christie, Leyburn and Bird, I agree that, for very high levels of MVA, field testing would be inconvenient. However, I wonder whether the capacity of the Grid system has now reached such a value that switchgear having relatively small MVA capacity could conveniently be tested direct from the 132 kV system via transformer, reactors and resistances only. I have recently been concerned with short-circuit testing on small circuit-breakers up to about 20 MVA, taking a supply for this purpose from the public network. It is possible that testing conditions would be no more onerous if switchgear up to 250 MVA were tested from the 132 kV system, where the short-circuit power available might be of the order of 3·5 MVA. It seems that the load on short-circuit testing plants might thus be reduced, enabling a greater use to be made for development tests on higher-voltage circuit-breakers of high breaking capacity, which could not be conveniently tested by any other method. What is the authors' opinion on this matter, and to what extent are high-power testing plants utilized for testing low- and high-voltage fuses and switchgear up to 250 MWA breaking capacity?

[The authors' reply to the above discussion will be found on page 726.]

## NORTH-WESTERN SUPPLY GROUP, AT MANCHESTER, 29TH MARCH, 1955

**Mr. V. A. Brown:** For some considerable time, the basis for proving large circuit-breakers will be single-phase testing in conjunction with unit testing. There is no doubt that single-phase tests at 1·5 times the rated voltage divided by $\sqrt{3}$ do produce stresses in excess of those encountered when testing a circuit-breaker 3-phase, and I agree that the factor of 1·5 should be reduced to 1·0 or at least 1·2.

Tests additional to those required by B.S. 116: 1952 are under

constant review, but as regards the various light-load switching tests, the precise circuit parameters and the criteria of success or failure are not yet definite enough, and, in consequence, it would be premature to standardize these as proving tests at the present time.

It is essential that at least one test at 100% rated symmetrical breaking current should be made with the trip-coil energized after the short-circuit has been established. This test will check whether the opening operation has been impeded by the possible additional stress imposed on the mechanism and contacts by the electromagnetic forces.

I do not agree that the restriking-voltage amplitude factor should be standardized for testing purposes, because this is only one of the two factors which produce the peak value of the restriking voltage. The other is the momentary recovery voltage, and therefore it is only necessary to prescribe the peak restriking voltage and not the amplitude factor on its own.

Another case of detailed specification is that of power factor. Any power factor between zero and 0·3 is adequate. Fig. C

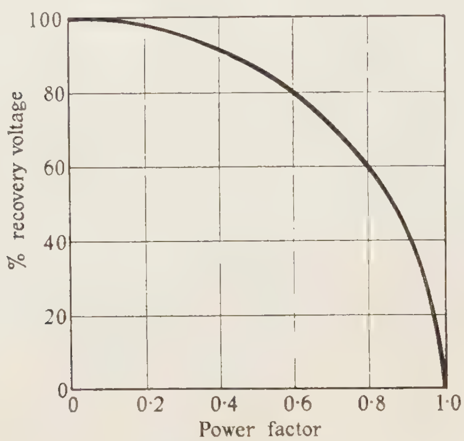



Fig. C

shows the relationship between recovery voltage and power factor, and up to a power factor of 0·3 the reduction of recovery voltage is less than 5%. For breaking tests there is no need to limit the power factor to 0·15. The wider tolerance, 0–0·3, gives greater freedom in adjusting test circuits. Furthermore, when breaking asymmetrical currents at the end of a major loop, a power factor of 0·3 gives a higher recovery voltage than any lower power factor because of the off-set current wave.

I am sympathetic to the proposal for increased flexibility in selecting the currents for the 30% and 60% test duties, but I think that further consideration of the detailed specification is needed to avoid a large gap between the 10% and 30% test duties when the 60% and 30% test duties are carried out at the highest values allowable by the proposal.

With regard to the proposed additional make-break test duty, this need not be additional if test duty 4(*a*) of B.S. 116 is done as a make-break duty with a time delay between the make and the break of the second make-break operation to allow the latching or free tripping of the circuit-breaker to be proved. A further reason for the make-break duty is to ensure that the circuit-breaker will make in the second make-break operation with burnt contacts, as in service.

A practical criterion for the existence of a critical current is whether the average value of the arc durations in the three 10% tests is greater than the average value for the three 30% tests.

In connection with over-voltages produced by light-load switching, the authors do not make it clear whether the normal phase-to-neutral voltages used in obtaining over-voltage ratios are peak or r.m.s. values.

I think that the authors have given the impression that the U-connection of the test generators produces a greater output, but it does not do so in its own right. The increased output results solely from over-excitation of the generator. The output from two lines of a star-connected stator or from two corners of a delta-connected stator is exactly the same as that produced when the U-connection is used at the same excitation for all three types of connection.

**Mr. M. A. Bird:** In Section 3.1 of the paper by Messrs. Christie, Leyburn and Bird, it is suggested that "in no case must the period of arcing be less than the normal period for the particular duty." Does this mean that the minimum arcing time should be greater than the duration of a major loop? Do the authors advocate that repeat asymmetrical tests should be made until this condition is satisfied?

Very-heavy-current asymmetrical tests are already difficult to execute, because of the small latitude of time for contact separation (relative to short-circuit initiation) if excessive peak currents are to be avoided on the one hand and the asymmetry is to be obtained on the other. For this reason, any changes to the British Standard which would add to this difficulty would not be welcome.

With reference to conventional oil circuit-breakers, it is often said that the 100% asymmetrical test can be regarded as ensuring a factor of safety on interrupting performance. I submit that in many cases the requirements of the 100% asymmetrical test lead to a circuit-breaker with reduced performance at the lower (10% and 30%) and more common short-circuit currents. In addition, they make the circuit-breaker more expensive. Have the authors any statistical evidence to show that 100% asymmetrical tests are unnecessary at any or all voltages?

With reference to Section 3.2.3, do the authors consider that a half-cycle reduction in arcing time by artificial reduction of test plant r.r.r.v. for 100% tests would be beneficial in enabling the low-current performance to be improved or the cost reduced? This only refers to tests done at full voltage and refers specifically to oil circuit-breakers, since r.r.r.v. reduction is already common practice for air-blast circuit-breakers.

In Section 4.10, I would support the authors' suggestion of a level of the order of $2V/\sqrt{3}$ for standard proving tests on very high-voltage circuit-breakers, and I feel that where higher recovery voltages occur in service, they should be regarded as an application problem, and a circuit-breaker of higher rated voltage should be used.

The authors state that recovery voltages of $3\cdot 47V/\sqrt{3}$ are rare because very-high-voltage systems are seldom earthed through arc-suppression coils and the fault conditions which produce such voltages are also uncommon. The first reason is fortunately true, but I am not so sure about the second reason. I believe that if the system conditions are such that by a fault and switching combination such a voltage can occur once, then it is likely to occur often. On a suitable network, such a voltage may arise if a single-phase intermittent earth fault (i.e. an arcing ground) occurs and produces a sufficient build-up of voltage on the healthy phases to cause another single-phase flashover to earth. If the protective gear which then comes into operation is not very fast, a circuit-breaker between the two faults may be subjected to voltages approaching $3\cdot 47V/\sqrt{3}$ or even more, since these networks are usually far flung and prone to regulation and Ferranti rise troubles. A factor of 3·7 has been recorded on more than one occasion.

In Section 5.5, the authors mention two points of particular

importance, but a third point is the voltage to be used for single-phase tests—in this case the test voltage should be about $1 \cdot 2V/\sqrt{3}$ both for line and capacitor-bank switching.

**Dr. H. F. Maass:** The paper by Messrs. Christie, Leyburn and Bird differentiates between proving and development tests. I wish to make a strong plea in favour of not treating all the proving tests discussed as suitable acceptance tests, fit to appear in standard specifications as type tests. The value of testing may be much enhanced by taking advantage of the flexibility of investigational testing and avoiding the rigidity necessarily associated with the performance of standard tests.

For example, Table 1 may be considered as a good guide to maximum values applicable to present or foreseeable future system conditions in this country. However, treating the values as mandatory for type-test circuits could lead to quite misleading results. R.R.R.V.'s in systems of lower load concentration, which are frequent oversea, are well below the quoted figures. Depending on the r.r.r.v. sensitivity of a circuit-breaker it may be desirable to test it for only one or for both conditions. Again, depending on the characteristics of a circuit-breaker, it may or may not be essential to take account of peak restriking voltage. More important still are the differences between the inherent and the actual restriking voltages caused by premature forcing of the current to zero or by shunt resistors and post-arc conductivity. As a result of such influences, onerous conditions may be met at other than top restriking-voltage frequencies. I contend that, in order to meet such conditions, flexibility of investigational testing is needed and that rigidly prescribed test conditions would be of little value.

The adoption of a test method tends to govern circuit-breaker design, possibly in a direction not leading to the best engineering solution. This consideration is again a reason for caution in adopting rigid test procedures and may be illustrated by Section 7.5, in which it is stated that the most acceptable solution to the problem of testing large circuit-breakers consists in single-phase unit-testing in high-power test plants. The economic impossibility of providing full-scale 3-phase test plants induces me to support this conclusion, but it may be as well to remember its limitations.

Unit testing is only applicable to multi-break circuit-breakers with enforced control of the voltage distribution over the breaks, the minimum number of which is determined by the test-plant capacity. The employment of forced voltage-distribution control necessitates the use of additional components which may not be free from trouble. Some other points already mentioned in the paper, in particular the choice of the appropriate single-phase test voltage, clearly present difficulties.

Unit testing does not overcome some of the drawbacks mentioned in the paper in connection with tests at reduced recovery voltages, such as the unrepresentative condition of the voltage between contacts and earthed metal. The voltage transfer conditions mentioned in Section 4.12 affect not only switching resistors, but also other control impedances and the insulation of the breaks themselves. Leaving the voltage distribution to establish itself naturally would be beneficial by shortening the duration of such conditions. Designs not amenable to single-phase unit-testing should not therefore be excluded from consideration.

With regard to the U-connection of test transformers discussed in Section 3.5 of the paper by Messrs. Christie, Leyburn and Fenn, I would refer to my discussion* before the C.I.G.R.É.

**Mr. E. W. Connon:** Switchgear testing and proving is of importance to the supply industry for two main reasons. First because we have to be certain that we have safe and reliable systems, and secondly because in the long run our consumers have to pay for the testing and testing facilities.

The need for large breaking capacities has greatly increased the cost of circuit-breakers, and it would be interesting if the authors could give some idea of what proportion of the cost is due to the proving and to the provision of testing facilities.

This greatly increased cost has led system design engineers to seek means of reducing to the minimum the number of circuit-breakers used on their systems, and it is obviously in the best interests of everyone that as much economy as possible should be exercised.

Circuit-breakers only carry out their full function under abnormal conditions, and we should never forget that this is so. It is only the weakness and failure of some other equipment which makes it necessary for them to carry out their full function.

Unfortunately, more frequently they have to be used for purposes for which their full capabilities are not required—I refer, of course, to their use for normal operational switching—and this is sometimes so because no other devices are available for this lower duty. The use of a 2 500 MVA circuit-breaker to switch out a transformer seems like using the proverbial steam hammer to crack a nut.

Therefore, I should like to feel that switchgear engineers were devoting a measure of their skill and testing facilities to the development of devices suitable for purely operational switching, since this would enable the system designer to limit the application of the expensive large circuit-breaker, with its expensive proving tests, to those situations where it is absolutely necessary. Perhaps standardization of test duties to cover this function would further such development.

Section 2.4 of the paper by Messrs. Christie, Leyburn and Bird is a valuable survey of the function of switching resistors, but from the application point of view, it would appear that the authors suggest that the different types of resistors call for different test duties. This, in turn, suggests that a circuit-breaker fitted with a particular type of resistor will only be suitable for a particular type of duty in service. With economic methods of system design, the same circuit-breaker may have to perform different functions, i.e. it may have to clear faults on several different types of circuit, which, from the foregoing, it would seem that it might not be able to do. Would the authors state whether this is so?

Short-circuit testing, by the authors' showing, has been carried out since 1929 to a continually improving standard. It is therefore disconcerting to find so much switchgear—not all of it very old—being derated at present by its manufacturers. Can the authors assure us that this will not recur in the future?

**Mr. R. W. Blower:** In Section 2.4(*a*) of the paper by Messrs. Christie, Leyburn and Bird, the authors state that resistors for controlling the r.r.r.v. should preferably provide critical damping at full fault current. I agree that this is preferable with air-blast circuit-breakers, but it has been proved for oil circuit-breakers that resistors designed to damp critically the restriking transient in the critical-current region result in a more uniform arc characteristic, the pressures developed in the arc control device at full fault current being able to cope with any r.r.r.v. without much help. This enables a larger resistance to be used—probably some thousands of ohms—and so eases the problem of resistor design and resistance current interruption.

I concur with Mr. Brown's comments on the making test, and I do not see that a case necessarily exists for a duplicate make-break–3 min–make-break duty. I think that a case exists for this duty to be performed as a make-break–3 min–make one, the clearance of the fault after the second break being either by the station master circuit-breaker or the circuit-breaker under test, after a delay long enough to allow satisfactory proof of

* *C.I.G.R.É. Proceedings*, 1954, **1**, p. 274.

latching. The break operation of the first test of this duty should follow as soon after the make as practicable in order to prove the interrupting performance of the arc control device in the presence of gases produced by pre-arcing, and the second make test will prove latching with roughened contacts.

In Section 4.13, the authors state that frequency effects fall outside the scope of the paper, but I am pleased to note that the subject has been mentioned if only to serve as a warning to those who may interpret the wide frequency tolerance allowed by standard specifications on circuit-breaker testing as meaning that frequency does not affect circuit-breaker performance.

Tests have shown that, if an oil circuit-breaker normally clears with arc durations between 0·03 and 0·04 sec at a given fault level on a 50 c/s supply, halving the frequency has little effect, but with other values there is always an increase in the range of the arc duration. In the case of an oil circuit-breaker clearing within the range 0·01–0·02 sec at full fault level, the increase of this range to 0·01–0·03 sec that would occur on a 25 c/s supply could well be serious, and steps have to be taken to allow for the increased mechanical stressing.

In Section 5.4, I do not agree that the number of major restrikes should be a part of the criterion of a circuit-breaker's performance when switching capacitance currents. Ideally the best and only certain criterion of performance on this duty is that the circuit-breaker should not restrike, but this is not always an economic or practicable proposition, particularly at the higher voltages.

When testing circuit-breakers for capacitance current interruption it is very important to study the way in which high-frequency charging current is interrupted. Some types of circuit-breaker are virtually incapable of clearing this current at a high-frequency current zero and so will never impose excessive over-voltages on the system, no matter how many restrikes occur. On the other hand, a circuit-breaker which does interrupt at the first high-frequency current zero may have a gap strength characteristic not conducive to high over-voltages.

These possibilities, in conjunction with a generally good service record, make it difficult to lay down what constitutes acceptable performance, and there is scope for more investigatio to find a suitable criterion.

It is also possible that in an endeavour to improve capacitanc switching by increasing the rate at which the electric strength the contact gap increases, increasing over-voltages may ari when interrupting small inductive currents.

Proving of switchgear for capacitor switching duty, as d scribed in Section 5.5, should include not only break tests, whe the problems are much the same as in the preceding Section, b also the way in which the contacts stand up to the repeate making duty with heavy inrush currents.

**Mr. A. J. Coveney:** I would like to emphasize two practic points of view. B.S. 116: 1929 was revised in 1936, and in 19 a completely enlarged and modern version was issued. I co sider that there should now be some stability in this wor Since the additional features which the authors suggest a mainly concerned with very high voltages and large capacitance would they agree that the present Standard should rema unaltered and that these modifications be dealt with under separate group. If this were decided, both the supplier and us would be more assured in their system planning and valuatic of existing switchgear.

With regard to the necessity which has arisen in the past o having to re-assess the circuit-breaker performances in line wi the modern specifications, this has entailed some considerab disturbance to existing layouts and caused costly modernizatio to take place. Can the authors give a simple, factual statemen comparing values, say, between these three specifications? consider that all pre-1929 circuit-breakers should be replace and those produced during the period 1929–36 should be reviewe and used possibly as either off-load isolators or non-automat circuit-breakers. The basis of all this work is essentially t provide safety to operators and maximum continuity of suppl and the simpler we can make these rules, the more readily the will be maintained. Have we now reached some reasonab finality in standards, so that we can enjoy a stable period for good many years to come?

## THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

**Messrs. J. Christie, H. Leyburn, J. F. Bird,** and **R. W. Fenn** (*in reply*): We have found it most convenient to reply under separate subject headings, stating the names of the contributors immediately following each heading.

*Single-phase Testing Voltages* (Messrs. Gosland, Baron, Peirson, Flurscheim, Cherry, Walshe and Brown): We propose to confine ourselves to the choice of testing voltage as applied to circuit-breakers intended for effectively-earthed systems, i.e. systems with multiple solidly-earthed neutrals. Fig. D illustrates the level of test voltages that might be adopted to cater for the various ranges of service conditions.

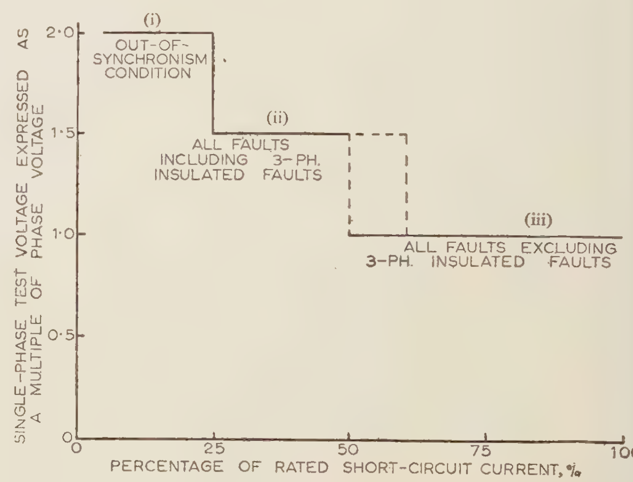



**Fig. D.**—Proposed single-phase test voltages for circuit-breake intended for use in effectively earthed systems.

With regard to the ranges (i) and (ii), although one or two speakers have expressed disagreement in detail, there is reasonable agreement on the principle. M. Baron refers to the possibility that "dynamic over-voltages" will cause a high recovery voltage. In our opinion this possibility applies only to ranges (i) and (ii), and the higher level of testing voltage proposed for these ranges should be adequate.

With one exception there is also agreement on the level for range (iii), or at least agreement on the desirability of reducing the testing voltage from 1·5 times the phase voltage to some lower level. The exception is Mr. Cherry who, although admitting that a 3-phase insulated fault upon which the factor of 1·5 is based "cannot occur (or nearly so) on a solidly earthed system," nevertheless wishes it to be retained as a factor of safety. We cannot see any justification for this item to be singled out for special treatment. Any reputable manufacturer has to ado such factors of safety as will enable him to demonstrate all th characteristics of a circuit-breaker without fear of failure. An additional factor of safety such as that advocated by Mr. Cherr would have the effect of producing a double factor of safet

ith a consequent unnecessary increase in the cost of the circuit-eaker. Mr. Cherry's statement that "the I.E.C. have adopted . . this offending factor" is not quite correct. In the Note to lause 60 of I.E.C. Publication No. 56 (1954) a reduced factor 1·3 is given, applicable under the conditions discussed here. 'e believe that even this reduction is inadequate and that a st voltage equal to the phase voltage is high enough to prove at the circuit-breaker can deal with all faults in an effectively-rthed system except 3-phase insulated faults. Space does not rmit us to give the technical arguments which have led us to is conclusion, but we hope that they will be dealt with at some ter date.

*R.R.R.V.* (Messrs. Gosland, Baron, Flurscheim, Mott, awkins, McQueen and Bird): There is fairly general agreement at the values of r.r.r.v. worked to hitherto in Great Britain e too high and that those proposed in Table 1 of the paper e more realistic. We note Mr. Mott's disagreement with our oposals, and all we can do is to reiterate that even second oughts have not shaken our belief that the values we have oposed are more than high enough for all reasonable service nditions likely to occur in the immediate or distant future. fact, a recent review of several power systems oversea, which e more loosely coupled than the British Grid system, leads us believe that, as mentioned by Mr. Flurscheim, there may ssibly be a case for alternative values of r.r.r.v. at a still lower vel.

*Developing Faults* (M. Baron): While so-called developing ults can occur there is not sufficient evidence that they are equent enough to be taken into account in the proving of cuit-breakers. We suggest that all that is required at the esent stage is the collection of further evidence in service.

*Three-phase versus Single-phase Tests* (Mr. Gosland): We ree that, in general, a single-phase test is more onerous than e corresponding 3-phase test.

*Test at 5% Rating* (Messrs. Peirson, Walshe, Buttrey and own): The object of the test at 5% rating is to prove the cuit-breaker in the "critical current" range. If, in a particular cuit-breaker, the critical current differs materially from the rrent corresponding to 5% or 10% of the rating, further tests ay be required.

*Auto-reclosing* (Messrs. Peirson and Care): In general, the ito-reclosing duty in a testing station should reproduce service nditions as closely as possible. It is impossible to state to at extent a circuit-breaker has to be de-rated as the number auto-reclosing shots increases, without knowing all the cir-mstances of the case.

*Testing of Oil Circuit-breakers at Reduced Voltage* (Messrs. osland and Mott): Fig. 2 is given merely by way of example. 'e agree with Mr. Mott, and we trust we have made it clear in e paper, that the results obtained when testing oil circuit-eakers (or for that matter any other breakers) at a greatly duced voltage may be misleading.

*Synthetic Testing* (Messrs. Gosland and Walshe): While not crying the value of synthetic tests for research and develop-ent, we consider that they are not yet sufficiently far advanced be used for proving purposes. The simulation of certain ltage conditions, as suggested by Mr. Walshe, may be useful more direct methods are not available.

*Line Switching* (Messrs. Hawkins, Brown and Blower): The ase-to-neutral voltages used in obtaining over-voltage ratios e peak values. We agree in the main with Mr. Blower's marks. The over-voltages generated when breaking line-arging current are the main criterion of success or failure; e number of major restrikes should be taken as a guide only.

*Switching of Zero-Sequence Currents* (Mr. Casson): There is difficulty in making a circuit-breaker capable of switching zero-sequence currents in excess of positive-sequence currents, provided that this requirement is known beforehand. Whether it can be met "at no extra cost" is another matter altogether.

*Basis of H.V. Circuit-breaker Design* (Mr. Cox): The suggestion that the design of large high-voltage circuit-breakers should be based on units of a standard size is one which will have to be given serious consideration eventually. We cannot, however, agree with the suggested standard sizes—for example, an air-blast circuit-breaker with a breaking-capacity of 15000 MVA, based upon the unit size of 1000 MVA, would consist of as many as 18 to 20 units per phase! Neither can we agree with Mr. Cox that "if these (unit) ratings are exceeded the operation becomes less predictable." That is not so, provided that the unit is proved by adequate tests.

*Effects of Switchgear Testing* (Mr. Bennett): It is gratifying to note that the general effect of short-circuit testing the earlier smaller switchgear has been in the direction of economy in space and cost rather than in the opposite direction, as was feared in the early days of switchgear testing. It is hoped that the present activity relating to the proving of large high-voltage circuit-breakers will eventually produce similar results.

*Fault-Current Release* (Mr. Buttrey): We agree that great care must be taken in proving tests to avoid the possibility of "blind spots."

*Unit Testing* (Mr. McQueen and Dr. Maas): Provided that the necessary precautions, for example as laid down in A.S.T.A. Publication No. 15, are observed, unit testing can be a reasonably true measure of full-scale testing. We agree that designs not amenable to unit testing should not be excluded from consideration, but the difficulties encountered in proving such designs can be very great indeed.

*Test Certificates* (Mr. McQueen): The modifications to a circuit-breaker which are permitted after a test certificate has been issued are confined to details not likely to affect its performance.

*Oil Maintenance* (Mr. Morley New): It is true that the aspect of oil maintenance is not covered by the standard tests, although it is customary to carry out additional tests on circuit-breakers of a type in which the degree of contamination of the oil is likely to differ materially from existing types.

*Switching of Shunt Reactors* (Mr. Care): We consider that circuit-breakers for the switching of shunt should be regarded as special. It would be uneconomic to include design features required for this duty in circuit-breakers for general application.

*Testing from the Mains Supply* (Mr. Care): If some of the smaller switchgear could be tested from the public mains supply it would relieve the pressure of work in high-power testing stations.

*Amplitude Factor and Test Duties* (Mr. Brown): We sympathize with the views expressed. Standardization of amplitude factor and test duties can be obtained only after thorough investigation by, and discussions between, all the interested parties.

*Asymmetrical Test* (Messrs. Gosland, Brown and Bird): We believe that, particularly with the slower circuit-breakers, an asymmetrical test is not required at all. When it is required, a clearer specification, as suggested in the paper, would help, although we agree that the whole subject bristles with difficulties.

*Development Tests* (Dr. Maas): It is unavoidable that some of the finer points are lost sight of when rigid proving tests are accepted as a basis of performance. We agree that these finer points must be taken care of during the development and investigational tests.

*Cost of Testing* (Mr. Connon): It is impossible to give the figures asked for, and we would refer Mr. Connon to our reply under the heading "Effects of Switchgear Testing."

*Switching under Load and Fault Conditions* (Mr. Connon): We doubt whether separating the functions of load switching and fault switching would lead to overall economy.

*Switching Resistors* (Messrs. Connon and Blower): We agree in the main with Mr. Connon's statements, although it is possible for some of the requirements (but not all) to be met by one particular type of resistor. Mr. Blower's comments are noted.

*Standard Specifications* (Mr. Coveney): Specifications dealing with the proving of breakers capable of being full-scale tested are not likely to change. This, however, cannot be said of the proving of large high-voltage circuit-breakers for which methods of testing have not yet teached finality.

*U-connection* (Messrs. Gosland, Peirson, Cliff, Cox, Morton and Brown): The U-connection is no more and no less than what it is said to be in the paper, namely a convenient "method of increasing the single-phase output at standard voltages." We agree that there are other methods of increasing the output by using over-excitation, but they usually deliver voltages which differ from the standard voltages. The testing station has now been in commission for just under two years and the U-connection has been used extensively for providing the highest single-phase outputs at the required voltages. We have not given much thought to the question raised by Mr. Peirson as to whether we would have adopted the U-connection and over-excitation if we had had an entirely free hand, because under the circumstances this question is rather academic; but the answer would probably be in the affirmative.

*Making Switch* (Messrs. Gosland and Cliff): Mr. Gosland is correct in his assumption that the accuracy of $\pm 10\%$ is an overall accuracy. This tolerance can be reduced considerably when doing a series of tests under specified conditions. Mr. Cliff's reference to the air-insulated making-switch at the testing station with which he is associated is noted. It is very simi to the making switch installed at the Hebburn Short-Circ Testing Station in 1929.

*Over-excitation and Super-excitation* (Messrs. Cliff a Hawkins): The comparison we gave was between over-excitati in the sense in which we defined it, i.e. when the field is boost prior to the application of the short-circuit, and super-excitati in which it is boosted during the short-circuit. The supe excitation referred to by the two speakers appears to be cross between these two kinds. The point we wished to bri out was that over-excitation of the kind defined requires smaller d.c. machine and has some other advantages. W disagree with Mr. Cliff that "to design modern short-circu testing generators without super-excitation is wasting both outp and money." This statement ignores the fact that the short a durations of modern circuit-breakers make it possible to u the sub-transient reactance of the generators instead of havi to rely upon super-excitation. Super-excitation is not provid in the most recent large testing station built in the United State

*Testing-Station Output* (Messrs. Cliff and Cox): Our intenti was to give the salient features of a modern testing station a not to compare its output with that of other stations. Mr. Clif figures of output are irrelevant. What matters is not the outp at generator voltages, which in most modern testing stations far in excess of requirements, but the outputs on the high-volta side of the power transformers. These we note are not given Mr. Cliff's contribution.

Although we agree that the output provided by the testi station envisaged by Mr. Cox will prove the size of unit up which he bases his design, we have already stated that we co sider the unit to be too small, and this therefore also applies the size of the testing station.

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Paper No. 1814 U
Apr. 1955

# THE INSTALLATION OF METAL-SHEATHED CABLES ON SPACED SUPPORTS

By W. HOLTTUM, M.Eng., Member.

*he paper was first received 5th November,* 1954, *and in revised form 5th January,* 1955. *It was published in April,* 1955, *and was read before the* UTILIZATION SECTION 14*th April,* 1955.)


## SUMMARY

The installation of cables above ground, mainly out of doors on ›oks on posts, is a construction which has been extensively employed th lead-sheathed power cables, and some of them have developed eath fractures, shown by compound leakage, as a result of flexing service caused by expansion and contraction with changes of nperature.

While electrical failures due to this cause have been few, the sirability of eliminating or minimizing such sheath fractures, with e resultant loss of compound and eventual possibility of the entrance moisture, needs no emphasis.

The design of such installations, in order to achieve this purpose, s apparently never received the attention which it merits in view of e large capital value involved.

The behaviour of cables installed in this way is examined theoretically d by reference to service installations, and the conclusion is reached at the length between supports is the most important factor; normal actice has been to make this too short.

A method is developed for determining for each cable what the inimum length should be, and other features of installation design e dealt with.

Aluminium-sheathed cables erected similarly are also discussed.

The conclusions are the author's responsibility, and intended to give lead to the industry in establishing much-needed recognized standards.


## (1) INTRODUCTION

The desirable features of any method of cable installation are aximum current-carrying capacity and long life. Apart from echanical damage, life may be limited by breakdown of the sulation due to inherent weakness or through the entry of oisture as a result of corrosion or mechanical failure of the ieath.

The paper is concerned with the last-named source of trouble, hich may be liable to occur with cables erected with inter- iittent support.

There can be little doubt that burying in the ground is the iethod of installation giving the most generally satisfactory onditions for cable operation. While erection in air nominally :sults in greater carrying capacity, this does not apply in xposed situations without sun shielding, which adds seriously both capital and maintenance costs. On the other hand, the bsence of the mechanical restraint of surrounding earth permits iovement due to expansion and contraction with changes of :mperature, which deforms the sheath and may lead eventually ) fracture.

A large amount of lead-sheathed power cable has been installed ut of doors above ground in this country supported by hooks n posts, and to a more limited extent on walls, and a material ortion of it has developed sheath fracture, indicated by the ppearance of cable compound on the surface. One user has :ported that, of 400 miles of such cable over 10 years old, pproximately 10% of the drum lengths are so affected.

Cases of cable failure due to this cause are rare, as the dis- harge of compound prevents the entry of moisture, or at any ıte sufficient to cause breakdown, so that even outdoor cables with such sheath fractures may continue without failure for periods of years. They must nevertheless be regarded as a potential source of trouble through entry of moisture when the discharge of compound has become sufficiently reduced, or through weakening of the insulation by excessive compound loss.

The variations of length caused by changes of temperature, due to load and ambient variations, normally result in bending of a lead-sheathed cable beyond the elastic limit of the sheath, and it cannot be claimed that it is possible with heavy load cycles to prevent eventual sheath failure. On the other hand, there is good reason to believe that by improved methods of construction this stage may be greatly deferred, if not entirely prevented, and that an economically satisfactory life may reasonably be anticipated. The onset of fracture will, of course, depend on the range and frequency of temperature variation, which cannot normally be foreseen, nor would it be possible to foretell the sheath life were these conditions precisely known.

Whatever views may be held as to the desirability of this method of installation, it may be assumed that circumstances will arise from time to time which result in its adoption, so that it is important that the construction which will give the longest life to the cable sheath should be known.

There has hitherto been no general recognition of guiding principles, nor are there any satisfactory rules for the construction that should be followed.

The importance frequently attached by users to neatness of appearance, which usually means avoidance of sag between supports, militates against sound construction. Fortunately, this requirement is mainly directed to cables installed indoors, where the temperature range is less than for outdoor use and trouble due to poor provision for expansion is infrequent, but one instance of particular interest is recorded.

The purpose of the paper, therefore, is to lead to the establishment of the most satisfactory methods possible in the light of available knowledge, though it is not claimed that the matter can yet be brought to complete finality.

The relevant features of constructional design are three: spacing of supports, form of support, and initial sag; and working rules for each of these are developed. In addition, for lead-sheathed cables there is the question of the most suitable sheathing alloy.

The opportunity is taken to deal with aluminium-sheathed cables, with which there has so far been comparatively little such experience. The problem here is different, in that the sheath may be treated as an elastic beam, and the contribution of the other components of the cable to its stiffness is negligible.

Each feature is dealt with in turn, first for lead and then for aluminium, and the conclusions are then summarized.

Support spacings for a representative selection of cables determined by the method in the paper are given in Tables 5 and 6.

## (2) METHODS OF INSTALLATION OTHER THAN BURYING IN THE GROUND

These fall into the classes of continuous and intermittent support.

Mr. Holttum is with British Insulated Callender's Cables Ltd.

In the first are: drawing into ducts or pipes; laying in concrete troughing, sand-filled or unfilled; laying in wood troughing, unfilled and normally supported on posts; and laying on shelves in station work.

In the second class are: supporting by cleats, which usually grip the cable sufficiently to provide some resistance to longitudinal movement; and supporting on hooks, in which case the only resistance to movement is friction and adhesion due to the compound in the protective finish.

Rigid cleating at intervals short enough to prevent lateral movement would be costly and is not normally attempted. Moreover, there would be difficulty with large cables in preventing longitudinal movement at the ends of a run. Laying in unfilled wood troughing is a method which has given good results, although irregular snaking occurs. It is, however, expensive, and there is nothing to show that it is better than intermittent support arranged to the best advantage, which would appear to be the most economical of any method of installation.

Laying in sand-filled troughing approximates to burying in the ground. In the other cases of continuous support, some movement will occur with load and ambient fluctuations, and in duct work, where the joints are installed in pits, temperature changes cause bending of the cable between duct and joint which has resulted in sheath fracture. The author is not aware of sheath fracture having been found with the other methods of continuous support, but it might be that the most onerous temperature conditions have not occurred, or that fractures have developed but not been found or become apparent.

With intermittent support, sheath fracture is unusual in indoor or sheltered situations and has only been found to be frequent with the wider temperature ranges caused by exposure.

It is, however, generally associated with spacing of supports so short that bending occurs in single spans at intervals, the rest remaining virtually straight. It is, therefore, a tenable hypothesis that intermittent support, of well-considered design, would give service as good as, or even better than, continuous support where movement is not prevented. Whether this is so can be ascertained only from long experience of improved methods.

## (3) METHOD OF APPROACH TO THE PROBLEM

A solution by direct experiment is not practicable on account of the wide variety of mechanical characteristics, and the need for heavy cyclic loading for a long period. On the other hand, for lead-sheathed cable the number and complexity of the factors involved prevents a theoretical solution devoid of approximations.

A theoretical approach, taking account as far as practicable of the mechanical characteristics, so that the results may fairly be regarded as comparable for different cables, is however possible.

This is the method which has been used. In addition, inspections have been made of a number of service installations, and the application to the cables in these of the method evolved suggests that it gives reasonable results and offers the prospect of much improved behaviour.

Aluminium-sheathed cable is amenable to purely theoretical treatment.

## (4) THE MECHANICAL BEHAVIOUR OF A CABLE NOT COMPLETELY RESTRAINED

Of the alternatives of continuous support with partial lateral restraint, as in a trough, and intermittent support on hooks or in cleats, the former leads to irregular "snaking" and is also much more costly. It is obviously desirable that expansion should be accommodated throughout the length in a regular manner to avoid local excess.

Intermittent support with lateral freedom between supports is therefore indicated, and the principal case to be dealt with is that of a fairly horizontal and straight run.

It is obvious that a primary consideration is the spacing of the supports. The form of support and the treatment of bends, gradients and terminations call for separate consideration.

The behaviour under expansion and contraction of a cable intermittently supported, and more or less free to move longitudinally, is subject to the following considerations:

If the supports closely embrace the cable and are near enough together to prevent lateral movement, the condition away from the ends is equivalent to burial in the ground, and expansion results only in longitudinal thrust. With increase of spacing, a point will be reached when each span becomes a strut stressed nearly to collapse; eventually bending will occur in single spans here and there, and these will accommodate the total expansion so that the rest remain virtually straight. The effect is shown in

Fig. 1.—Diagram of cable showing collapsed span.

Fig. 1. Sometimes deflection in opposite directions occurs in two adjacent spans, forming an S-bend.

With further increase of spacing, another critical point will be reached at which the weight of the cable is just sufficient to cause enough sag in each span to accommodate its expansion. There will then be no tendency to lift or slip at supports, or longitudinal stress due to expansion. This is to be regarded as the minimum permissible spacing short of complete restraint.

If the spacing is still further increased, the weight will be more than sufficient to cause the necessary sag, and will result in tension, though of a small order compared to the compression under complete restraint.

The primary object is, therefore, to be able to determine, for any cable, as nearly as possible, that minimum spacing at which the weight of the cable will cause just sufficient sag to accommodate the expansion.

There is probably some advantage in exceeding this minimum, as the curvature produced by a given amount of expansion is less the greater the span. In addition, the curvature produced in a cable initially straight is greater than the increase of curvature produced by the same amount of expansion in a cable having an initial sag. It is, of course, the change of curvature during operation which is important and not the total curvature.

## (5) EXPERIMENTAL WORK

Two experimental investigations thought likely to assist in formulating conclusions were made.

A suitable value for the amount of longitudinal expansion must be employed. The conductor, sheath and armour of a lead-sheathed cable tend to expand by different amounts, and the resultant expansion of the cable is not theoretically determinable because the amounts of slack in the conductor and armour wires are unknown and variable, and the rate of creep of the sheath depends upon the stress. Tests were therefore

arried out (see Section 16.1) on lengths of 33kV 3-core and 1kV 3-core cable, before and after removal of the wire armour.

The conclusion was reached that, for 3-core and s.l. solid-type ables, an expansion of 0·04% can reasonably be adopted as a tandard value, and 0·06% for single-core cables.

Somewhat higher values would be appropriate for oil-filled r gas pressure cables which operate at higher conductor temerature, and 0·05% and 0·075% are suggested.

The other experiment (see Section 16.2) was to find by obseration, for six different lead-sheathed cables, the span at which ne cable ceased to be able to support its own weight without agging; the criterion used was the span at which a sag of 1·0% ccurred in 8 hours at ambient temperature.

The test was difficult to conduct with precision, and the ratio f test span to calculated span varied from 1·21 to 1·53 with a nean of 1·41. This suggests some degree of comparability, nd that the calculated spans, while a good deal greater than sual practice, are not excessive.

## 5) SERVICE EXPERIENCE WITH LEAD-SHEATHED CABLES

Seventeen installations of interest, supplied by 8 cablemakers, vere inspected, as given in Table 1.

The procedure generally followed was to select a length of normal run, preferably showing compound leakage if occurring, and measure spans and sags for about a dozen spans, noting special features. The support spacings between centres, calculated by the method in the paper, are tabulated together with the actual spacings, making use of cable data supplied by the user, or, where these were not available, assuming the most likely dimensions for the size and date of manufacture.

It will be seen that 11 of the items had evidence of sheath fracture; four showed irregular mechanical behaviour which might be expected to lead to sheath fracture; and three, having wider support spacing, showed no unsatisfactory features.

Nos. 7*b*, 11 and 16, the satisfactory cases, had support spacings 1·12, 1·09 and 0·81 times the calculated value. No. 16, however, had been only lightly loaded, so under more onerous conditions might have behaved differently, though light loading had not been found to give immunity from signs of developing trouble, e.g. Nos. 15 and 17.

7*b* and 11 had been well loaded and were very old cables; the sheaths were of unalloyed lead, which is not to be regarded as suitable for the purpose. It is notable, therefore, that the two cables showing conspicuously good behaviour had support spacings rather greater than the calculated values.

Both these cables were on walls, the first being sheltered by a

**Table 1**

INSTALLATIONS INSPECTED, WITH ACTUAL AND CALCULATED SUPPORT SPACINGS

| Item No. | Year | Area | Voltage | Sheath: Alloy | Sheath: Bore | Sheath: $t$ | Armour wires: Diameter | Armour wires: No. | Weight | Support spacing: Actual | Support spacing: Calculated | Ratio nom./calc. | Behaviour |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | in² | kV | | in | in | in | | lb/in | in | in | | |
| 1 | 1916 | 0·2 | 11 | Pb | 2·10 | 0·16 | 0·16 | 53 | 1·198 | 63 | 89 | 0·71 | L |
| 2 | 1916 | 0·1 | 11 | Pb | 1·83 | 0·14 | 0·16 | 45 | 0·905 | 66 | 86 | 0·77 | L |
| 3 | 1929 | 0·25 | 11 | Pb | 2·106 | 0·13 | 0·192 | 43 | 1·189 | 66 | 90 | 0·73 | L |
| 4 | 1926 | 0·15 | 11 | Pb | 1·828 | 0·12 | 0·192 | 39 | 0·957 | 66 | 88 | 0·75 | L |
| 5 | 1924 | 0·3 | 11 | Pb | 1·906 | 0·109 | 0·104 | 59 | 0·812 | 66 | 79 | 0·84 | L |
| 6 | 1941 | 0·2 | 11 | C | 1·625 | 0·125 | 0·128 | 48 | 0·767 | 42 | 74 | 0·57 | L |
| 7*a* | 1916 | 0·094 | 11 | Pb | 1·813 | 0·14 | 0·1 | 62 | 0·697 | 75 | 86 | 0·87 | L |
| 7*b* | 1916 | 0·094 | 11 | Pb | 1·813 | 0·14 | 0·1 | 62 | 0·697 | 96 | 86 | 1·12 | S |
| 8 | 1930 | 0·2 | 11 | C | 1·95 | 0·125 | 0·192 | 38 | 1·064 | 48 | 85 | 0·57 | L |
| 9 | 1925 | 0·1 | 11 | Pb | 1·671 | 0·12 | 0·16 | 41 | 0·772 | 66 | 82 | 0·80 | I |
| 10 | 1939 | 1·4 | l.v. | D | 1·765 | 0·15 | — | — | 0·907 | 48 | 98(E) | 0·50 | I |
| 11 | 1904 | 0·15 | 11 | Pb | 2·07 | 0·14 | 0·128 | 60 | 0·923 | 96 | 88 | 1·09 | S |
| 12 | 1933 | 0·2 | 11 | C | 1·95 | 0·14 | — | — | 0·681 | 42 | 86 | 0·49 | L |
| 13*a* | 1933 | 0·25 | 11 | B | 1·89 | 0·12 | 0·192 | 39 | 1·060 | 54 | 114 | 0·47 | L |
| 13*b* | 1933 | 0·25 | 11 | Pb | 1·852 | 0·12 | 0·192 | 38 | 1·037 | 54 | 86 | 0·63 | I |
| 14 | 1936 | 0·15 | 11 | Pb | 1·87 | 0·13 | 0·128 | 40 | 0·790 | 51 | 82 | 0·62 | L |
| 15 | 1931 and 1936 | 0·2 | 11 | Pb | 1·95 | 0·13 | 0·192 | 34 | 1·033 | 48 | 88 | 0·55 | I |
| | | | | E | | | | | | | 102 | 0·47 | |
| 16 | 1931 | 0·25 | 11 | Pb | 2·06 | 0·13 | 0·192 | 36 | 1·127 | 72 | 89 | 0·81 | S |
| | | | | E | | | | | | | 103 | 0·70 | |
| 17 | 1931 | 0·25 | 33 | ½C | 2·613 | 0·14 | 0·128 | 69 | 1·109 | 42 | 118 | 0·36 | see note |

All 3-core cable except No. 10 which is single-core.
L—Leaking compound, generally at spans showing excessive bending.
I—Irregular formation, with occasional excessive bending which might lead to sheath fracture.
S—Satisfactory.

*Notes regarding Individual Items*

7*b*. Installed under the edge of a station platform, so fairly sheltered; well loaded.

10. Bad support alignment due to post settling and tilting. This had assisted the cable to bend in many spans so that severe local bending was avoided. The cable was so stiff in relation to its weight that gravity had negligible effect, and spans were bowed in all directions.

13*b*. Pre-impregnated cable, so probably sheath fracture would not lead to compound leakage. The irregularity was similar to that in 13*a* on which two leaks were seen.

14. Many compound leaks, sometimes several in a span and in consecutive spans; also in straight runs.

15 and 16. Sheath alloy unknown, so calculated for lead and E alloy; lightly loaded. 15 lifted from support at two positions.

17. Sun-shielded and only lightly loaded. At bends near joints longitudinal movement indicated by disturbed serving.

station platform. No cable on posts in the open, other than No. 16, was found to be free from undesirable features.

While at first sight these two cases may be thought to be rather slender evidence of the benefits of wide spacing, the other installations strongly support this conclusion, since their unsatisfactory features were clearly associated with the shortness of the spans.

Moreover, the author has been unable to find a single case of a well-loaded cable intermittently supported in the open with the conventional short spacing which was behaving satisfactorily. Except for Nos. 7*b*, 11, and 16, sliding on or lifting from supports, or local bending absorbing the expansion of a number of spans, were generally observed.

The conclusion is unavoidable that the main factor leading to sheath fracture is supports too near together.

Of 38 leaks at noted positions, 17 were at midspan, 9 near a support, and the remaining 12 at various positions, 10 in the middle half. While maximum flexing occurs at the supports in independently sagging spans, it is more likely to take place at mid-span in spans absorbing more than their share of expansion. Since fracture is therefore most likely at these latter positions, the above distribution compares reasonably with expectation. Also, since thermal expansion will increase compression and reduce extension, it is to be expected that fractures would first develop at concave surfaces. As these are the underside at supports, the appearance of compound would be encouraged at the point of fracture rather than travelling to the lower part of the span before finding its way out. It has not been possible to check these points, except that, in the cables referred to at the end of Section 12, the fractures were mainly at concave surfaces.

It will be appreciated that, while more detailed and precise observations of longitudinal movement and change of sag with variations of temperature would have been of interest, there was a practical limit to facilities for observation. Moreover, such information would be of academic interest only, as the observations made were adequate for their purpose.

An opportunity was, however, taken to measure sags on a dozen spans at two widely differing temperatures on installation No. 9, and the values obtained (Table 2) afford interesting confirmation of the expected cable behaviour.

The first measurements were in warm and sunny weather with a cable surface temperature of 92°F. The second were bright cold weather, the cable surface being at 41°F.

The following, among other, points of interest may be observe While the ratio of increase of sag from cold to warm should greater the smaller the sag, and for the mean values this is s individual spans show a different result. For feeder 1, t smallest cold sag of 1·09% increased only 13%, while the large of 1·80% increased 41%. For feeder 2, the smallest, 0·94% increased 8%, and the largest, 1·62%, increased 38%. Th clearly indicates movement lengthways on the hooks.

In this Section, and as an item of history, reference may made to certain "compromise installations" where methods ha been employed which would certainly not be repeated.

In one case, 14 miles of 0·2in² 11kV 3-core wire-armour cable was laid on continuous battens 3in wide on posts, an clamped at intervals of 3ft. In warm weather the cable snak off the battens, so three gaps of 9ft were put in the battens p drum length of 250yd, two years after installation. This kept t cables on the battens, but as each gap had to accommodate t expansion of 83yd, compound leakage due to sheath fracture the gaps was reported after a further 10 years.

In the other case, 14 miles of 0·2in² 33kV 3-core wir armoured cable was laid on battens with 3 expansion gaps 9ft per drum length of 220yd. In spite of sun-shielding, an again in 10 years, the same trouble showed up. Supports 2½ high at 9ft centres were then inserted to lift the cable clear of t battens. After six more years no further trouble had been reporte and it would seem probable that this is a satisfactory solutio

A typical case of collapsed span showing compound leaka is shown by Fig. 2. Station cabling showing collapse in t bottom cable of a trefoil group is shown by Fig. 3. T

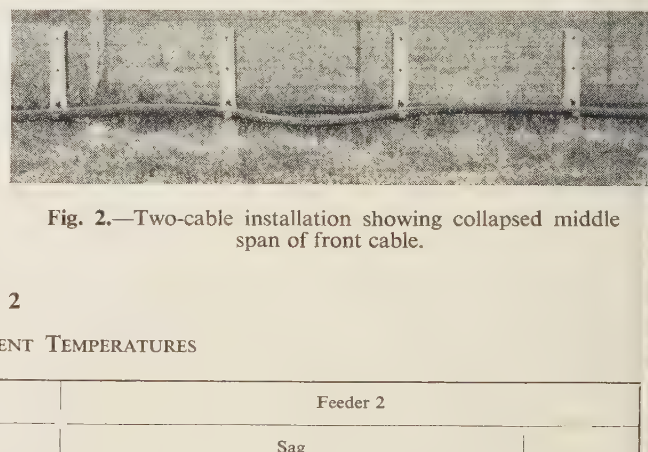
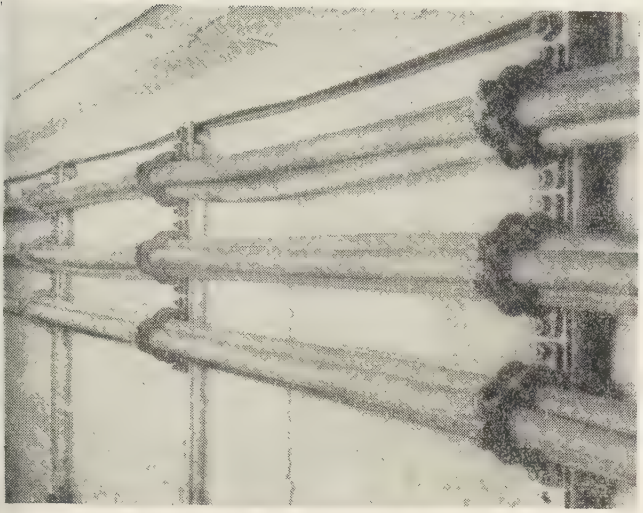


**Fig. 2.**—Two-cable installation showing collapsed middle span of front cable.

**Table 2**

Sags at Two Different Temperatures

| Span | | Feeder 1 | | | | | Feeder 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sag | | | | Ratio warm/cold | Sag | | | | Ratio warm/cold |
| | | Cold | | Warm | | | Cold | | Warm | | |
| No. | Length | Length | % of span | Length | % of span | | Length | % of span | Length | % of span | |
| | in | in | | in | | | in | | in | | |
| 1 | 67·3 | 0·90 | 1·34 | 1·15 | 1·71 | 1·28 | 0·90 | 1·34 | 1·56 | 2·32 | 1·73 |
| 2 | 63·8 | 0·98 | 1·54 | 1·27 | 1·99 | 1·30 | 0·60 | 0·94 | 0·65 | 1·02 | 1·08 |
| 3 | 66·5 | 0·85 | 1·28 | 1·08 | 1·63 | 1·27 | 0·85 | 1·28 | 1·16 | 1·74 | 1·36 |
| 4 | 68·0 | 1·08 | 1·59 | 1·45 | 2·13 | 1·34 | 0·80 | 1·18 | 1·04 | 1·53 | 1·30 |
| 5 | 65·8 | 0·90 | 1·37 | 1·10 | 1·67 | 1·22 | 0·99 | 1·50 | 1·28 | 1·95 | 1·29 |
| 6 | 64·9 | 0·85 | 1·31 | 1·06 | 1·64 | 1·25 | 0·70 | 1·08 | 0·77 | 1·19 | 1·10 |
| 7 | 66·4 | 0·90 | 1·35 | 1·15 | 1·73 | 1·28 | 0·78 | 1·17 | 0·95 | 1·43 | 1·22 |
| 8 | 66·4 | 0·97 | 1·46 | 1·20 | 1·81 | 1·24 | 0·99 | 1·49 | 1·40 | 2·11 | 1·42 |
| 9 | 65·8 | 0·92 | 1·40 | 0·95 | 1·44 | 1·03 | 0·75 | 1·14 | 0·80 | 1·22 | 1·07 |
| 10 | 67·3 | 1·21 | 1·80 | 1·71 | 2·54 | 1·41 | 1·09 | 1·62 | 1·50 | 2·23 | 1·38 |
| 11 | 64·2 | 0·70 | 1·09 | 0·79 | 1·23 | 1·13 | 0·65 | 1·01 | 0·94 | 1·46 | 1·45 |
| 12 | 66·8 | 1·00 | 1·50 | 1·40 | 2·10 | 1·40 | 1·00 | 1·50 | 1·35 | 2·02 | 1·35 |
| Mean .. | | 0·94 | 1·42 | 1·19 | 1·80 | 1·26 | 0·84 | 1·27 | 1·12 | 1·69 | 1·31 |



g. 3.—Cable tunnel installation showing collapse, in top group, of bottom cable in near span; top cable in far span; and, in middle group, all cables in far span.

pport spacing was 3 ft; the cable was $0\cdot6\,in^2$ single-core $6\cdot6$ kV ıalloyed lead-sheathed, for which the calculated spacing is in. The mechanical behaviour of these cables was such that ey were replaced by those referred to in Section 12 before ıeath fracture developed.

## (7) CREEP OF LEAD AND ITS ALLOYS

It is well known that lead and its alloys have no definite yield ress; plastic deformation commences at a stress of the order of 00 lb/in$^2$, and the rate depends upon the stress, the temperature, ıd the physical condition of the material. The determination f the rate at which an intermittently-supported tube or rod ill sag under its own weight is therefore a matter of some omplexity. With a cable, the matter is further complicated by e other components and the friction between them.

With a given stress, the initial rate of creep may be several mes the value to which it settles down after the metal has eveloped a strained condition. After a period of rest, the itial, or some intermediate, rate will obtain.

Obviously, the minimum creep rate is the value which is of iterest for the present purpose, since sooner or later the sheath likely to reach the strained condition to which this applies.

While a great amount of research into rates of creep has been arried out, the available information useful to the present urpose is very limited. Stress/minimum-creep curves for lead nd several alloys were, however, fortunately available, and xamination of these showed that the rate of creep can be xpressed as $10^{As-B}$, where $s$ is the stress and $A$ and $B$ are constants.

An interesting feature of the behaviour of lead and its alloys that, although the range of sheath temperature of a buried able is such that without restraint the length would vary so ıuch that the complete longitudinal restraint under which it perates is equivalent to stressing well beyond the elastic limit, o sheath fracture has been traced to this cause. A temperature hange of about 14°C would result in a stress of 1 000 lb/in$^2$ if ıe material did not yield. The explanation of the apparent reedom from trouble from this cause must be regarded as bscure.

## (8) SUPPORT SPACING

From the foregoing it is clear that the support spacing should epend upon the cable weight and stiffness, the measure of the tter being the ratio of bending moment to curvature. It will lso depend upon the amount of expansion and, for lead-sheathed cable, the rate of expansion, since this will affect the stress and so the required bending moment. No simple relation between spacing, and dimensions and weight is, therefore, possible, and the matter is dealt with as follows:

### (8.1) Lead-Sheathed Cable

While lead- or alloy-sheathed cable is by no means an elastic beam, and very slight bending will be beyond the elastic limit of the sheath except for a small region about the neutral plane, it is convenient to treat it as an elastic beam in computing the relation between extension, sag and curvature. This will represent its behaviour fairly closely, and can be assumed to give results comparable for different cables.

The total bending moment is determined by summating the bending moments for the metallic components. For the conductor and armour wires this is straightforward, as any curvature will be well within the elastic limit, but for the sheath, which makes much the largest contribution, the bending moment will depend upon the rate of bending and the temperature, as well as the material.

While the non-metallic components of a cable will make some contribution, and while this will be relatively greater the smaller the conductors for a given voltage, it may reasonably be assumed to have no serious effect on the comparability of results for different cables. The ignoring of this component of the total bending moment should result in a conservative value of the support spacing arrived at. In spite of this, the method developed gives support spacings substantially greater than those which have most usually been employed, and comparable with those used on satisfactory installations.

Regarding temperature, it might be claimed that the lowest during operation should be taken, since the rate of heating for a given load will be little affected by temperature, and the greatest resistance to natural sagging will therefore occur at the lowest temperature.

The lowest temperature for which the required stress/creep curves were available was 25°C, but it may be argued that this is a not unreasonable value to adopt.

The method of calculation employed assumes that the cable is straight when cold. Actually, even if a cable is installed straight, it will after a time develop a sag in each span. In addition, it is recommended later that it should be installed with an initial sag. If there is a sag when cold, the amount of bending required to accommodate a given expansion is greatly reduced.

Moreover, in the early life of an installation, the loading is likely to be low. The important considerations are that the support spacings arrived at should be comparable for different cables and should be reasonable in the light of experience. Creep data for 25°C will, of course, comply with the first condition, and are found to comply with the second.

Examination of the stress/creep curves for 25°C shows that the rates of creep expressed as $10^{As-B}$, where $s$ is the stress and $A$ and $B$ are constants, are as given in Table 3.

Table 3

CREEP CONSTANTS OF LEAD SHEATHING ALLOYS

| Material | Creep % per hour |
|---|---|
| | Exponent of 10 |
| Lead | $s/138-6\cdot3$ |
| Alloy B ($0\cdot85$% Sb) | $s/557-4\cdot59$ |
| Alloy C ($0\cdot4$% Sn + $0\cdot15$% Cd) | $s/536-2\cdot24$ |
| Alloy ½C ($0\cdot2$% Sn + $0\cdot075$% Cd) | $s/259-5\cdot42$ |
| Alloy E ($0\cdot4$% Sn + $0\cdot2$% Sb) | $s/253-5\cdot82$ |
| Alloy $0\cdot1$% Sn | $s/211-5\cdot4$ |

It is necessary also to assume a rate of bending which is determined by the increase in length and the length of time in which it occurs. While this rate will not be uniform, it is found that if the fractional increase of length of 0·0004 is assumed to take place in 4 hours, the consequent average rate gives reasonable results. The sheath bending moment, therefore, is computed by allowing for the stress as determined by the average rate of creep for each part of the section. The curvature is then determined on the assumption that the cable takes the form of an elastic beam having the same length and the same extension.

On this principle, the following formula has been arrived at, taking logarithms to the base 10 and all dimensions in inches, where the symbols have these meanings:

$L$ = Distance between centres of supports.
$D_i$, $D$, and $D_o$ = Sheath inner, mean and outer diameters.
$t$ = Sheath mean thickness $= \frac{1}{2}(D_o - D_i)$.
$w$ = Cable weight, lb/in.
$A$, $B$ = Creep constants for sheath material.
$n$ = Number of conductor wires.
$c$ = Diameter of each conductor wire.
$m$ = Number of armour wires.
$a$ = Diameter of each armour wire.

$$L^3 - 12D^2tL[U + B - \log L + (D_o^3 \log D_o - D_i^3 \log D_i)/6D^2t]/wA = V(9nc^4 + 11ma^4)10^6/w \quad (33)$$

The derivation is given in Section 16.5.

For unarmoured cable, the term $11ma^4$ will vanish. The constants $U$ and $V$ will have the following values according to the appropriate amounts of expansion $e$:

| Cable | $U$ | $V$ | $e\%$ |
|---|---|---|---|
| Solid type, 3-core and s.l. . . . . | 0·43 | 0·48 | 0·04 |
| Solid type, single-core . . . . | 0·52 | 0·59 | 0·06 |
| Gas pressure or oil-filled, 3-core . . | 0·48 | 0·54 | 0·05 |
| Gas pressure or oil-filled, single-core | 0·57 | 0·66 | 0·075 |

For s.l. cable, calculate for one core with one-third of the armour wires, and multiply the result by 1·5.

Inserting values for a particular case reduces the equation to the form

$$L^3 - FL(G - \log L) = H$$

which is easily solved for $L$ by trial. The term $FL(G - \log L)$ provides for the bending moment due to the sheath, and $H$ for that due to the wires.

There is no reason to think that substantial increase of spacing beyond the critical length would be harmful. It would have the merit of reducing the variation of curvature with expansion in the inverse ratio of the spacing.

In the case of s.l. cable the formula must be applied, in effect, to one core, so that the weight and number of armour wires to be taken is one-third of those for the whole cable. The result of the test in Section 16.2 suggests that the assembly of the three cores together does not result in disproportionate increase of stiffness; but, on the other hand, observations on a service installation having a span slightly greater than the calculated value indicate longitudinal movement. It is therefore proposed that the minimum support spacing for s.l. cables should be 1·5 times the calculated figure.

While the method developed above may seem somewhat complicated, the formula, once available, is easily applied to any particular case. The value of some of the constants is apparently not critical, though this may be less true for some parts of the range of cable types and sizes. An attempt at simplification is therefore not justified, since the comparabili of results for different cables would in some degree be lo without compensating advantage.

Table 4 shows the effect upon the calculated span of varyin the assumed expansion and period of heating $h$.

**Table 4**

CALCULATED SPANS FOR DIFFERENT AMOUNTS OF EXPANSIO AND RATES OF HEATING FOR LEAD AND 3 ALLOYS

| $e\%$ | $h$ | 0·6-in² L.V. 3-core | | | | 0·1-in² 33-kV 3-core | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Pb | B | C | E | Pb | B | C | E |
| 0·02 | 2 | 73·9 | 108·4 | 74·1 | 88·6 | 86·1 | 133·9 | 86·1 | 106·9 |
| 0·06 | 2 | 80·1 | 114·0 | 82·5 | 94·1 | 90·8 | 139·2 | 94·0 | 111·0 |
| 0·04 | 4 | 76·4 | 108·2 | 74·8 | 90·0 | 86·9 | 131·8 | 84·4 | 106·8 |
| 0·02 | 6 | 71·7 | 102·3 | 66·4 | 85·3 | 83·0 | 125·8 | 74·8 | 102·4 |
| 0·06 | 6 | 78·3 | 108·3 | 75·7 | 91·0 | 87·8 | 131·4 | 83·8 | 107·0 |

As already indicated, the calculated spacing is to be regarde as a minimum, and the author's opinion is that a considerab increase beyond this would not be harmful.

There can be no critical upper limit other than that impose by the tensile strength of the cable, but, with spans of suc length that settlement occurs to approximate catenary formatio cyclic bending at the ends calls for consideration.

The change of mid-span curvature with expansion is muc less than the change of curvature for a beam of even the sam length, so the important point is the change of slope at th ends, which for 0·04% expansion, and percentage sags of 0, or 5 is, in radians, 0·049, 0·014, or 0·006.

Taking 2% sag, the change of curvature for a beam 100 long is, from Table 7, 0·12/100 and so the length of unifor curve for 0·014 rad at this curvature would be 0·014 100/0·12 = 11·7 in. While extensions to the supports to contr the curvature for this length might be provided, it seems like that the 0·014 rad, or 0·8°, would be distributed over a sufficie length to involve no serious hazard.

Another line of argument is that since, for overhead line changes of length are accommodated without serious concen tration of bending at supports, it seems a fair assumption th the greater stiffness of a cable would result in the bending bein distributed over a correspondingly greater length, making equally innocuous.

While, therefore, very long spans would in many cases b inconvenient, operational conditions should be satisfactor with spans and sags for which a suitable support can be provide and the tension is acceptable to the cable.

This refers to fairly level runs. For steep gradients th span would form part of a catenary with large sag, the lowe point being outside the span. The formulae for small sag woul therefore cease to be applicable.

Where different cables are run on the same post route, an theoretically require different support spacing, a proble arises as to the most economical arrangement.

A reasonable rule would be that, if the shortest calculate span is not less than half the longest, all the cables runni together should be erected with the longest span. This would i time provide valuable experience, with much less risk than wit the short spans used in the past. If the shortest is less than ha the longest span, then an intermediate support at the middle o each long span could be provided if desired.

It is obviously undesirable that one cable should be supporte from another.

Table 5 gives span lengths for a representative selection of ıbles to B.S. 480 determined by the method proposed.

**Table 5**

'ALCULATED SPANS FOR 3-CORE SOLID-TYPE CABLE WITH ALLOY E SHEATH AND SINGLE-WIRE ARMOUR

| Voltage | 1·1 kV, belted | | | 11 kV, screened | | 33 kV, screened | |
|---|---|---|---|---|---|---|---|
| Conductor area in$^2$ .. | 0·1 | 0·3 | 0·75 | 0·1 | 0·5 | 0·1 | 0·5 |
| Span, in .. | 63·5 | 76·1 | 92·4 | 77·8 | 93·0 | 104·1 | 114·6 |

### (8.2) Aluminium-Sheathed Cable

Aluminium-sheathed cable will behave as an elastic beam for a ınge of bending which, with suitable design, will absorb the ꭓpansion. The sheath will control its mechanical behaviour, nd the stiffness of the conductor, and armour, if any, are comıaratively negligible and can be ignored.

Experience with aluminium-sheathed cables with intermittent ıpport is still limited, but it may be said that three principles f accommodating expansion, which may be designed to operate ithin the elastic limit of the sheath, are available as follows:

(*a*) Beam construction, with the supports spaced so that each ɔan will take up its expansion by sagging under its own weight.

(*b*) The provision of expansion bends, each of which accomıodates the expansion of a number of spans.

(*c*) Strut construction, in which the cable is clamped at each ıpport and given an initial deflection up and down in alternate ɔans. The expansion is accommodated by further bending in ach span.

#### 3.2.1) Beam Construction.

Hooks are adequate during operation, but clamps may be vanted to facilitate installation.

In most, if not all, cases the straight length between supports ecessary to enable the weight to cause sufficient sag to accomıodate the expansion results in a stress beyond the elastic limit. 'he necessary length of span can be reduced to less than this ritical length by the provision of initial sag when installing. It vill, of course, considerably exceed the length required for ead- or alloy-sheathed cables.

Only experience will show whether long spans resting in hooks re specially liable to disturbance through careless treatment or ıterference, but this would not seem likely.

The maximum span for the weight to cause stress within the lastic limit is given by eqn. (15).

The maximum expansion for elastic accommodation from the traight length is given by eqn. (16). If the actual expansion xceeds this, as is usual, the initial sag required for the selected pan, which must not exceed that from eqn. (15), is given by qn. (17).

#### 3.2.2) Expansion Bend Construction.

Expansion bend construction involves sliding of the cable on he supports, and space to accommodate each bend, which hould preferably be sufficiently long and offset from the ne of the cable run to accommodate the expansion within the lastic limit of the sheath. The supports are hooks in which he cable is free to slide, with the exception of a flat horizontal upport at the middle of the expansion bend and a clamp midvay between expansion bends. The thrust is balanced, so the lamps may be designed for unit safety factor on the calculated hrust, except the end ones which should have a safety factor of wo.

The expansion bend will result in some bending of the span adjacent to each end of it, though not sufficient for it to behave as a strut with pivoted ends. The dimensions for pivoted and aligned ends are therefore computed, and, as the adjacent spans are much shorter than the expansion span, more weight is given to the aligned condition, and each dimension is taken as $\frac{1}{3}(2A + P)$, where $A$ and $P$ are the dimensions for aligned and pivoted ends respectively.

The length of expansion bend required for a given initial deflection is obtained from eqn. (28) by trial, and the deflection after expansion from expression (29). Alternatively, the initial deflection required for a given length of bend is found from eqn. (28) by direct solution.

A disadvantage of this construction is that, in order to keep within the elastic limit of the sheath, the expansion bends may be inconveniently large. Movement slightly exceeding the elastic limit may, however, be tolerated.*

The use of extruded sheathing, which is less work-hardened, would require larger expansion bands than for "died down" sheath, since the modulus of elasticity is little affected, while the yield stress is reduced. This position would be somewhat mitigated by taking advantage of any work-hardening which results from movement in service.

#### (8.2.3) Strut Construction.

Where it is desired to space the supports more closely than beam construction will permit, and to avoid expansion bends, strut construction can be adopted. The method is to have a hook midway between each pair of clamps, pulling the cable upwards and downwards in alternate spans. After straightening, the cable is placed in the clamps and in each hook, and thus given an initial offset as each span is placed in position. The offset at each hook is made sufficient to provide any initial deflection necessary for expansion within the elastic limit, with a minimum of, say, 3 in.

The system is more convenient on walls than on posts, where the deflecting hooks would require additional supports. For the same minimum curvature, the span length for strut construction is under one-third of that for beam construction, since for the latter there are two points of inflexion per span, while for the former there is one at each support only. The cable must, however, be clamped on account of the longitudinal thrust, which, while independent of the amount of deflection and theoretically balanced, might lead to irregularity.

The minimum initial deflection for a given spacing is found from eqn. (17), or, alternatively, the minimum spacing for a given initial deflection.

Only the end supports, where the thrust is unbalanced, need be designed for the full load, and the intermediate supports may be lighter.

In many cases of aluminium-sheathed cable indoors, expansion will be conveniently accommodated by bends in the run. Each such case should be treated on its merits and checked for elastic accommodation. For long runs approximating to straight, however, beam construction is to be recommended. Strut construction requires many more supports of greater unit cost, and also the intermediate hooks, and it is not apparent in what circumstances it would be justified, though experience may reveal other considerations.

An example worked out for each method is given in Section 16.6, and Table 6 gives span lengths for a representative selection of cables to B.S. 480 determined by the proposed method.

It will be noted that the initial deflection for 144 in span is in some cases excessive, indicating that this span is too short.

* HOLLINGSWORTH, P. M., and RAINE, P. A.: "Aluminium-Sheathed Cables," *Proceedings I.E.E.*, Paper No. 1638 S, April, 1954 (101, Part II, p. 603).

Table 6

CALCULATED SPANS FOR BEAM CONSTRUCTION FOR 3-CORE ALUMINIUM-SHEATHED CABLE

| Voltage | 1·1 kV, belted | | | 6·6 kV, belted | | 22 kV, screened | |
|---|---|---|---|---|---|---|---|
| Conductor area, $in^2$ .. | 0·1 | 0·3 | 0·75 | 0·1 | 0·5 | 0·1 | 0·5 |
| Maximum span, in .. | 212 | 225 | 272 | 273 | 277 | 372 | 372 |
| Initial deflection, in .. | 2·0 | 3·9 | 6·4 | 1·8 | 5·1 | 2·7 | 6·1 |
| Initial deflection for 144 in span.. .. | 6·8 | 11·9 | 25·3 | 12·8 | 22·8 | 32·2 | 50·3 |

Pilot and communication cables, being affected by ambient temperature only, operate under much easier conditions than power cables. As they are usually much smaller, they will have a shorter calculated span, but when run along with power cables they may reasonably receive the same support spacing, or, if run independently, a spacing well above the calculated value.

## (9) FORM OF SUPPORT

### (9.1) Lead- or Alloy-Sheathed Cable

None of the installation defects could be associated with the form of support.

Hooks varied from 2in to 6in in axial length, the majority being 3–4in. This dimension had no apparent relation to either cable diameter or support spacing. Some were castings with or without longitudinal curvature, and some were of bent strip with fairly sharp corners. The shortest were of the latter type, being 2in long for item 6 and 3in for item 8.

For an expansion of 0·04% starting from straight, the theoretical radius of curvature at the support is $2\cdot44L$ and the sag $0\cdot0128L$. If the sag were $0\cdot05L$ (greater than any observed) the radius would be $0\cdot625L$, which, from the point of view of the support design, means negligible curvature.

These figures, however, assume the geometry of an initially straight elastic beam, and, to show how near this is likely to be to the actual form, Fig. 4 shows a span measured on item 11

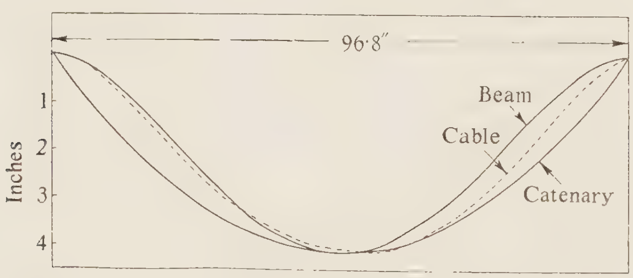



Fig. 4.—Form of sagging cable in comparison with beam and catenary.

Vertical scale = horizontal scale × 8.

in Table 1, together with the form of the beam and catenary for the same sag. The lack of symmetry is probably due to initial set, resulting in the cable sloping slightly on the right-hand hook. As would be expected, the shape is nearer to the beam than the catenary.

Fig. 5 shows part of this cable run. The installation was an old one with a large span, so that settlement was probably complete. It also had much the largest sags observed. The radius of curvature at the supports was not less than 16in. The minimum theoretical beam radius was 68·6in, so that settlement had increased the minimum curvature to about four times. A longitudinal curve to fit a radius of 16in would result

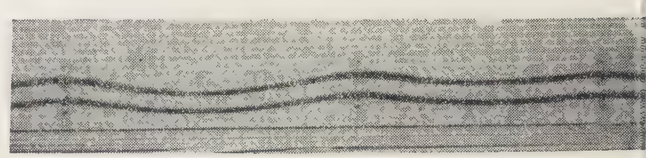


Fig. 5.—Cable taking up expansion by sagging in each span.

in the middle of the 3in long hook being 0·07in higher than t ends.

Longitudinal shaping of hooks not exceeding 3in may concluded to be unnecessary, though, if they are cast, the oppo tunity may be taken to give the bottom a longitudinal radi not less than one-sixth of the span. The edges should, in a case, be radiused $\frac{1}{8}$ in to prevent any sharp indentation damage to the serving during installation.

The axial length of support should be related to the beari pressure on the sheath, so that standard ranges of hooks a cleats should be designed for the heaviest span for each diamet The application of eqn. (33) shows that, for given sheath dime sions, span length varies proportionately less than cable weig per inch, so that the heaviest cable for a given sheath has al the greatest weight per span. Standard supports should the fore be designed for low-voltage unarmoured cable; they w then be adequate for any cable (armoured or not) of the sar overall diameter, as the addition of armour increases the diame more than the span weight.

The length of support required will depend on whether t cable is fairly closely embraced or rests on open or flat-bottom hooks. In the former case, the weight may be taken to distributed over 0·6 of the sheath diameter and in the latter, 0·1

From the calculated spans for low-voltage cables it is fou that a practically straight-line relationship exists between shea diameter and support length for a given pressure in pounds p square inch.

The following formulae for overall length of hook or cle give a bearing pressure, for armoured or unarmoured cabl not exceeding $85 lb/in^2$ on 0·6 of the sheath diameter, the 0·25 allowing for $\frac{1}{8}$-in radius at the ends, and $D$ being the over diameter:

*Three-core cable*

$$0\cdot43\,(D - 0\cdot4) + 0\cdot25\,\text{in}$$

*Single-core cable*

$$0\cdot4\,(D - 0\cdot3) + 0\cdot25\,\text{in}$$

*Single-core cable laid in trefoil*

$$0\cdot6\,(D - 0\cdot3) + 0\cdot25\,\text{in}$$

Where a length over 3in is required, the support shou preferably be longitudinally curved, and for open-hook or fla surface support the factors should be multiplied by 4.

Cables of diameters above the low-voltage range should treated individually, and a check on any large installation of particular cable may indicate possible economy.

Supports which grip or encircle the cable are required on where a tendency to move has to be restrained.

Where three single-core cables run in trefoil or flat formati as a 3-phase circuit, they must usually be held together to res the force of separation under short-circuit at more freque intervals than supports are required. Suitable binders or met straps will then suffice, without encircling or gripping clea though these may be a convenience as they are sometim helpful during installing.

For spans greatly in excess of the minimum so that the cab will settle towards catenary formation, the longitudinal radi

f support for bearing pressure $p$ per unit length and tension $T$ hould be

$$T/p = wL^2/8pY$$

The slope at the ends of a catenary is arc tan $4Y/L$ when $Y/L$ small, or $4Y/L$ radians nearly, so the bare length of support fit the cable, which should be exceeded by, say, 1 in each end nd radiused $\frac{1}{8}$in, should be

$$\frac{wL^2}{8pY}\frac{4Y}{L} \times 2 = \frac{wL}{p}$$

hich gives the correct bearing pressure.

### (9.2) Aluminium-Sheathed Cable

The pressure due to a hook having any flat axial length cannot e excessive, the only limitations being that the support should ot be a line contact, and that the edges should be radiused $\frac{1}{8}$in or the same reason as for lead-sheathed cable. Where gripping eats are required, the range for lead-sheathed cable would oubtless be used and would be of ample length.

For expansion bend construction, the hooks should have not ss than about 1 in axial length to facilitate sliding and minimize ear.

## 0) THE CASE FOR INITIAL SAG FOR LEAD-SHEATHED CABLE

It has already been pointed out that the curvature produced y expansion is less the greater the initial sag. The amount of he reduction for 0·04% expansion is shown in Table 7.

Table 7

EFFECT OF INITIAL SAG ON CHANGE OF CURVATURE CAUSED BY EXPANSION

| Initial sag, % of span . . | 0 | 0·5 | 1·0 | 2·0 | 3·0 | 4·0 | 5·0 |
|---|---|---|---|---|---|---|---|
| Curvature at support × $L$: | | | | | | | |
| Initial . . . . | 0 | 0·16 | 0·32 | 0·64 | 0·96 | 1·28 | 1·60 |
| After 0·04% expansion | 0·41 | 0·44 | 0·52 | 0·76 | 1·045 | 1·345 | 1·65 |
| Extra curvature due to expansion . . . . | 0·41 | 0·28 | 0·20 | 0·12 | 0·085 | 0·065 | 0·05 |

If, therefore, a cable is installed with an initial sag of 2·0%, the ffect is to reduce the bending by more than two-thirds of what it ould be starting from straight, or, for 0·5% initial sag, the eduction is still nearly one-third.

There is therefore a case for installing a lead- or alloy-sheathed able with an initial sag in order to reduce the amount of flexing f the sheath in service, and 2% of the span is suggested as a uitable amount.

Observations of installed cables, confirmed by the test recorded n Section 16.1, indicate that sag develops or increases during ervice, apart from further increase by settlement towards atenary formation.

## (11) HANDLING OF CABLES DURING INSTALLATION

*Lead-Sheathed Cable.*—Cable along a railway may be paid ff a drum mounted on a railway wagon moving along the oute, or may be man-handled from a drum in a fixed position. n either case, the cable must be laid in the hooks progressively rom one end. If, as recommended, initial sag is to be provided, agging should be carried out manually about two spans behind he last hook in which the cable has been laid. A straight-edge vith a projection at the middle equal to the required sag will be seful, and it may be necessary to hold down each span while the ext one is sagged.

*Aluminium-Sheathed Cable.*—There has been some difficulty with beam construction in achieving regularity, particularly where two or more cables are run together, and lack of uniformity may be unsightly. It is the author's view that straightforward methods of producing satisfactory results will be evolved by experience.

For long runs, there is a material saving of labour by running the cable through a straightening device as it leaves the drum.

It has been found advantageous to grip the cable at each support in order to control it properly. Such gripping is not required during operation, so that at most temporary clamping would suffice.

For expansion bend construction, where the supports are much nearer together, the difficulty of installation is less, as should also be the case for strut construction.

## (12) SHEATH MATERIAL FOR LEAD-SHEATHED CABLES

A choice should eventually be made of the most suitable alloy, i.e. that which will best stand up to slow repeated bending beyond its elastic limit. Available information appears to give no clear guide. Fatigue-limit values, being determined for comparatively rapid cycles of stress, cannot be regarded as conclusive.

The alloy should also be resistant to vibration, as many cables above ground are subject to this in some degree; but the incidence of sheath fracture which has been observed indicates that flexing and not vibration is the primary, if not the only, cause, since it generally occurs in spans where bending has concentrated. Long experience with different alloys under similar conditions may be required in order to establish a definite choice, but further research is needed.

Meanwhile, alloy E, which is a popular alloy and easily extruded, is suggested as a reasonable choice, unless users like to try others. There is the following reason to believe that alloy E is better than unalloyed lead.

In 1944 some 6·6kV 0·75in² single-core alternator cables were installed in a power station tunnel, 9 cables for each of 2 alternators in trefoil cleats at 72in nominal centres. The cables for one alternator are sheathed with alloy E and for the other with lead. The loading has been about the same in each case, with daily cycles from zero to a little over half full rating in summer, and $\frac{3}{4}$ full rating in winter. After about 8 years, sheath fracture commenced to develop on the lead-sheathed cables, but no trouble has yet been reported with the alloy-E sheath. This occurred in the warmest part of the tunnel.

## (13) CABLE RUNS OTHER THAN HORIZONTAL AND STRAIGHT

Sagging between supports under gravity is the most simple and effective means of taking up expansion. Departures from straightness are therefore less simple to deal with vertically than horizontally. For the latter, the support spacing on straight runs should be maintained where convenient, as bends capable of being self-supporting are best left free, though closer spacing is permissible. In some cases, a flat support at mid-span may help, with provision for sliding laterally, and such spans may be longer.

Curves in a sloping or vertical plane should be cleated no more frequently than is required for stable positioning, thus allowing freedom for expansion.

On a slope, the bending moment for a given span is reduced in the ratio of the cosine of the angle $\alpha$ of the slope. The equivalent span length, $L_s$, is therefore given by $(wL_s^2 \cos\alpha)/12 = wL^2/12$, so that

$$L_s = \frac{L}{\sqrt{\cos\alpha}}$$

This makes little difference for moderate angles.

For vertical runs, alternative methods of providing for expansion are erection with an initial deflection or, for wire-armoured cable, suspension from the armour terminated in a cone clamp, with a large free bend at the bottom to absorb the expansion.

The former method is to bow the cable in opposite directions alternately between successive cleats, which may be spaced according to the weight each will support, but the greater the spacing the easier will be the setting of the cable during erection. A deflection of 5% of the cleat spacing is suitable, and for this the cleats should be at an angle of about 11°, or for 10% deflection about 23°.

Single-bolt fixing is convenient to enable each cleat to set itself to the cable, and this may be arranged by means of a back plate with a bolt hole on the centre line. Cleating would be carried out from the bottom, with the cable eased off from the top as required.

The method is also applicable to steep slopes, say above 60°, where gravity sagging may be doubtful.

The author is not aware of a case of expansion trouble on a steep or vertical run, even in the absence of precautions. Such cables are usually sheltered and cooled by ventilation, and long runs with a severe temperature cycle may be rare. It is, however, worth while to assess the operating conditions of such a proposed installation with some care to ensure the avoidance of expansion trouble.

## (14) CONCLUSIONS

The incidence of sheath fracture with lead- and alloy- sheathed cables run on spaced supports is generally due to the support spacing being too short, so that expansion results in localized flexing.

Features of the design of such installations have been considered, and the following guiding rules for lead- and aluminium-sheathed cables have been reached:

*Lead-Sheathed Cables.*

*Sheath material.*—Alloy E suggested, until information is available of the most suitable alloy for repeated slow flexing (Section 12).
*Support spacing.*—For 3-core and single-core cables, from eqn. (33); for S.L. cables, the same multiplied by 1·5.
*Initial sag.*—2% of support spacing (Section 10).
*Form of support.*—See Section 9.
*Runs other than fairly horizontal and straight.*—See Section 13.

*Aluminium-Sheathed Cables.*

*Support spacing.*—(Calculated example in Section 16.6.)
1. *Beam construction.*—Hooks so spaced that the expansion is taken up by sagging under gravity. Initial sag generally necessary for elastic accommodation. For maximum length for stress within elastic limit see eqn. (15). For maximum expansion for elastic accommodation from straight see eqn. (16). If expansion exceeds this, select span within length (15), and find necessary initial sag from eqn. (17).
2. *Expansion bend construction.*—Expansion bends at 50 yd intervals. Cable clamped midway between bends. Formulae are given in Section 16.4.
3. *Strut construction.*—Cable clamped at each support, and offset up and down in alternate spans by hooks midway between supports. Formulae are given in Section 16.4.
*Form of support.*—See Section 9.
*Runs other than fairly horizontal and straight.*—See Section 13.

## (15) ACKNOWLEDGMENTS

Acknowledgment is made to British Insulated Callender's Cables Ltd. and the Railway Executive, the London Transport Executive, the London Electricity Board, and the South Eastern Electricity Board and members of the Cable Makers' Association for kindly providing facilities for the inspection of their cables, and to the author's colleagues for co-operation with the experimental work.

## (16) APPENDICES

### (16.1) Increase of Length due to Thermal Expansion

The change of length with temperature of 12 ft samples two cables was measured, both with and without wire armour

Relative longitudinal movement of the metallic compone was prevented by an alloy-filled metal cap on each end.

The cable was supported on rollers in an electrically hea oil-bath.

Conductor heating appeared impracticable, but the abse of the temperature gradient occurring in service did not prev useful conclusions being drawn.

No observable tendency to twist occurred.

The cables were $0{\cdot}15\,\text{in}^2$ 3-core 11 kV and $0{\cdot}3\,\text{in}^2$ 3-core 33 each screened, single-wire-armoured and served.

The results given in Table 8 are corrected for possible sour of error.

**Table 8**

CHANGE OF LENGTH WITH TEMPERATURE IN TEST SAMPL

| | 11 kV | 33 k |
|---|---|---|
| Expansion coefficient per °C × $10^5$ armoured | 1·477 | 1·39 |
| Expansion coefficient per °C × $10^5$ unarmoured | 1·536 | 1·59 |
| Fractional permanent expansion × $10^5$, armoured | 60·0 | 36·1 |
| Number of cycles . . . . . . . . . . | 3 | 2 |
| Increase in last cycle . . . . . . . . | 8·9 | 0 |
| Fractional permanent expansion × $10^5$, unarmoured | 29·0 | 97·3 |
| Number of cycles . . . . . . . . | 2 | 3 |
| Increase in last cycle . . . . . . . . | 0 | 18·8 |
| Total fractional permanent expansion × $10^5$ . . | 89·0 | 133·4 |
| Sheath material . . . . . . . . . . | Lead | Alloy |

Linear expansion coefficients × $10^5$ per °C of metallic parts: conductor 1·77, sheath 2·90, armour 1·17.

The lower expansion of the 33 kV cable suggests that it h the tighter armour, especially as it had the harder sheath, a this is corroborated by its greater increase of expansion removing the armour.

Both with and without armour, the expansion was alwa between the values for conductor and armour, and so below values for both conductor and sheath.

The permanent component of the expansion is notable. is much greater for the 33 kV cable, and equal to the theoreti sheath expansion for 46°C.

Consideration of these results with the temperature rises the metallic components occurring in service has led to the co clusion that for solid-type cable 0·04% is a fair value to take the change of length in the operating temperature range. T applies to 3-core or s.l. cable, and 0·06% is proposed for sing core cable where the straight conductor is likely to have mo influence.

### (16.2) Tests for Natural Sagging of Lead- or Alloy-Sheath Cables

Lengths of six different cables were supported on rollers brackets, and the spacing was varied to find that at which a s 1·0% of the span developed in 8 hours.

Expansion of 0·04% corresponds to a sag of 1·28%, which assumed for calculation to take place in 4 hours. As the te were made at ambient temperature, the span for 1·0% sag 8 hours was made the basis of test.

Table 9 includes comparison of the test and calculated spa

**Table 9**

SPANS FOR 1% SAG IN 8 HOURS

| No. | Conductor area | Cores | Voltage | Sheath | | | Armour wires | | Wt. | Span | | Test/calculated span |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Alloy | Bore | Mean $t$ | Diameter | No. | | Test | Calculated | |
| | in² | | kV | | in | in | in | | lb/in | in | in | |
| 1 | 0·3 | 4 | l.v. | E | 1·741 | 0·105 | S.T.A. | | 0·695 | 111 | 92 | 1·21 |
| 2 | 0·25 | 3 | 11 | Pb | 1·788 | 0·105 | 0·104 | 68 | 0·744 | 115 | 75 | 1·53 |
| 3 | 0·06 | 3 | 11 | Pb | 1·228 | 0·084 | 0·104 | 50 | 0·377 | 93 | 67 | 1·39 |
| 4 | 0·3 | 3 | 33 | E | 2·648 | 0·135 | 0·128 | 72 | 1·365 | 151 | 111 | 1·36 |
| 5 | 0·5 | 1 | 33 | E | 1·597 | 0·105 | — | — | 0·475 | 143 | 97 | 1·47 |
| 6 | 0·25 | 3-S.L. | 33 | E | 1·550 | 0·095 | — | — | 1·25 | 127 | 85 | 1·49 |
| | | | | | | | | | | | | Mean 1·41 |

### (16.3) Geometry of Elastic Beam, Uniformly Loaded, having the Ends held Horizontal, but Free to move Longitudinally, and the Effect of Expansion

If $L$ is the length between supports, and $w$ the loading per unit ngth, the bending moment at distance $x$ from either end may e shown to be given by

$$w(L^2 - 6Lx + 6x^2)/12$$

he curvature at any point is then given by

$$M/EI = w(L^2 - 6Lx + 6x^2)/12EI = d^2y/dx^2,\ dy/dx \text{ being small} \quad (1)$$

here $E$ is Young's modulus and $I$ the moment of inertia of the ection. From this

$$dy/dx = w(L^2x - 3Lx^2 + 2x^3)/12EI \quad (2)$$

nd

$$y = w(L^2x^2/2 - Lx^3 + x^4/2)/12EI$$

nd so for $x = L/2$

$$y = Y = wL^4/384EI \quad (3)$$

he standard formula for the deflection of such a beam.

The beam length $S$ and the straight distance between supports re negligibly different for the purpose of the above formula, ut the difference between them is required in dealing with cable xpansion.

ow

$$ds^2 = dx^2 + dy^2$$

r

$$ds/dx = \sqrt{[1 + (dy/dx)^2]} = 1 + \tfrac{1}{2}(dy/dx)^2$$

$y/dx$ being small.

hen

$$S = \int_0^L [1 + \tfrac{1}{2}(dy/dx)^2]dx = L + \tfrac{1}{2}\int_0^L (dy/dx)^2 dx$$

utting $(S - L)/L = e$,

$$eL = \tfrac{1}{2}\int_0^L (dy/dx^2)dx$$

ence from (2),

$$= \frac{1}{2L}\frac{w^2}{144E^2I^2}\int_0^L (L^2x - 3Lx^2 + 2x^3)^2 dx$$

$$= \frac{w^2}{288E^2I^2L}\int_0^L (L^4x^2 + 9L^2x^4 + 4x^6 - 6L^3x^3 + 4L^2x^4 - 12Lx^5)dx$$

$$= \frac{w^2L^6}{288E^2I^2}\left(\frac{1}{3} + \frac{9}{5} + \frac{4}{7} - \frac{3}{2} + \frac{4}{5} - 2\right)$$

$$= \frac{w^2L^6}{288E^2I^2}\frac{1}{210}$$

$$= \frac{w^2L^6}{60\,480\,E^2I^2} \quad (4)$$

From (1) when $x = 0$, the radius of curvature is

$$R = 12EI/wL^2, \text{ or } EI = wL^2R/12 \quad (5)$$

Substituting this in (4)

$$e = \frac{w^2L^6}{60\,480}\frac{144}{w^2L^4R^2} = \frac{L^2}{420R^2} \quad (6)$$

Substituting from (5) in (3)

$$Y = \frac{wL^4}{384}\frac{12}{wL^2R} = \frac{L^2}{32R} \quad (7)$$

Substituting for $L$ from (7) in (6)

$$e = \frac{32EY}{420R^2} = \frac{8Y}{105R} \quad (8)$$

and substituting for $R$ from (8) in (7)

$$Y = \frac{105eL^2}{256Y} \quad (9)$$

The four quantities $e$, $L$, $R$, and $Y$ are obviously determined by any two of them, and from eqns. (7), (8), (9), and (6) it follows that

$$L^2 = 32RY \quad (10)$$

$$8Y = 105eR \quad (11)$$

$$256Y^2 = 105eL^2, \text{ or } Y = 0{\cdot}64IL\sqrt{e} \quad (12)$$

$$L^2 = 420eR^2, \text{ or } L = 2R\sqrt{(105e)} \quad (13)$$

For an elastic tube, the conditions for expansion to be taken up by elastic deflection under its own weight may be found as follows:

$g$ = Yield stress, lb/in².
$L_e$ = Minimum span at which expansion can be elastically accommodated, in.
$L_g$ = Span at which yield stress is just reached, in.

To find $L_e$, maximum stress $D_oE/2R = g$, so $R = D_oE/2g$.

Substituting in (13)

$$L_e = D_o E\sqrt{(105e)}/g \quad . \quad . \quad . \quad . \quad . \quad (14)$$

To find $L_g$

$$wL_g^2/12I = 2g/D_o$$

from which

$$L_g^2 = 24gI/D_o w \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

By equating the expressions for $L_e$ and $L_g$, solving for $e$ gives its upper limit for accommodation of expansion by elastic deflection, starting from straight, thus

$$105E^2D_o^2e/g^2 = 24gI/D_o w$$

from which

$$e = \frac{8g^3I}{35E^2D_o^3w} \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

By inserting the values of $g$ and $E$, the limiting value of $e$ in terms of dimensions and weight is found. If $e$ then exceeds this value, $L_e$ will exceed $L_g$, and the expansion cannot be elastically accommodated. This assumes straight formation initially. If, however, an initial deflection exists, the additional deflection and curvature required to accommodate the expansion will be less than that required if straight initially, and it may be possible thus to bring the bending due to expansion within the elastic range.

If $h$ is the initial deflection required to enable the weight to cause further deflection sufficient to accommodate the expansion, the extra length due to $h$ is, from eqn. (12),

$$256h^2/105L^2$$

$L$ having a value not exceeding $L_g$.
Deflection which weight can produce $= wL^4/384EI$.
Total deflection then $= h + wL^4/384EI$.
Extra length due to this, from eqn. (12)

$$= 256(h + wL^4/384EI)^2/105L^2$$

So extra length available to accommodate expansion

$$= 256(h + wL^4/384EI)^2/105L^2 - 256h^2/105L^2$$

Equating this to $e$ and solving for $h$ gives

$$h = 315EIe/4wL^2 - wL^4/768EI \quad . \quad . \quad . \quad . \quad (17)$$

The above formulae are directly applicable to aluminium-sheathed cable, but for lead-sheathed cable the further development given in Section 16.5 is required.

### (16.4) Geometry of Elastic Strut with Pivoted Ends, and the Effect of Expansion

If $L$ is the length, $D_o$ the diameter (outer for tube), $W$ the load, $y$ the deflection at distance $x$ from the end, and $Y$ the deflection at the middle, then the bending moment $M = Wy$; also

$$1/R = M/EI = Wy/EI = -d^2y/dx^2$$

Putting $k^2$ for $W/EI$, $\quad d^2y/dx^2 = -k^2y$

so

$$y = A\sin kx + B\cos kx.$$

When $x = 0$, $y = 0$, so $B = 0$, and when $x = L/2$, $y = Y$ so $Y = A\sin kL/2$ or $A = Y/\sin kL/2$

Hence

$$y = \frac{Y\sin kx}{\sin kL/2}, \quad \text{and} \quad \frac{dy}{dx} = \frac{kY\cos kx}{\sin kL/2}$$

To find length in terms of span, use the formula

$ds/dx = \sqrt{[1 + (dy/dx)^2]} = 1 + \frac{1}{2}(dy/dx)^2$, $dy/dx$ being small.

Then

$$S = \int^L [1 + \tfrac{1}{2}(dy/dx)^2]dx = L + \tfrac{1}{2}\int_0^L \frac{k^2Y^2\cos^2 kx}{\sin^2 kL/2}dx$$

so $2(S - L) = 2eL$

$$= \frac{k^2Y^2}{\sin^2 kL/2}\left[\int_0^L \tfrac{1}{2}(\cos 2kx + 1)dx = \tfrac{1}{4}\sin 2kx + x/2\right]_0^L$$

$$= \frac{k^2Y^2}{\sin^2 kL/2}(\tfrac{1}{4}\sin 2kL + L/2)$$

Now when $x = L/2$, $dy/dx = 0$, so $\dfrac{kY\cos kL/2}{\sin kL/2} = 0$

Hence $\tan kL/2 = \infty$, so $kL/2 = \pi/2$, and $k = \pi/L$.
Therefore $W/EI = k^2 = \pi^2/L^2$, so $W$ is constant, independent of $Y$.

Then

$$2eL = \frac{\pi^2Y^2}{L^2}(0 + L/2) = \pi^2Y^2/2L$$

and so

$$Y = 2L\sqrt{e}/\pi$$

Now

$$R = EI/WY = L^2/\pi^2Y = \frac{L^2}{\pi^2}\frac{\pi}{2L\sqrt{e}} = \frac{L}{2\pi\sqrt{e}}$$

giving the four relationships $L^2 = \pi^2RY \quad . \quad . \quad . \quad . \quad . \quad (18)$

$$Y = 4eR \quad . \quad . \quad . \quad . \quad . \quad (19)$$

$$4eL^2 = \pi^2Y^2 \quad . \quad . \quad . \quad . \quad . \quad (20)$$

$$L^2 = 4\pi^2eR^2 \quad . \quad . \quad . \quad . \quad . \quad (21)$$

Also the load, or thrust $\quad W = \pi^2EI/L^2 \quad . \quad . \quad . \quad . \quad . \quad (22)$

and maximum stress $= D_oE/2R$ which, from eqn. (4),

$$= \pi ED_o\sqrt{e}/L$$

At yield stress, $\pi ED_o\sqrt{e}/L_g = g$, so $L_g = \pi ED_o\sqrt{e}/g \quad . \quad . \quad (23)$

a useful expression for the minimum length for elastic accommodation of expansion without initial deflection. If it is desired to employ a length less than this, the necessary initial deflection $j$, is found as follows:

Where the initial deflection is produced by pressure at mid-length, the form will be that of a beam with central load, but as it can be shown that the length taken up by a given deflection is only 1·5% less for such a beam than for a strut, it is treated as a strut for convenience. For deflection, $j$, extra length from eqn. (20), $= \pi^2j^2/4L^2$, and maximum curvature, from eqn. (18) $= \pi^2j/L^2$.

Extra length to be accommodated after expansion

$$= \pi^2j^2/4L^2 + e$$

Curvature due to this, from eqn. (21),

$$= \frac{2\pi}{L}\sqrt{(\pi^2j^2/4L^2 + e)} \quad . \quad . \quad . \quad . \quad (24)$$

So extra curvature due to expansion

$$= \frac{2\pi}{L}\sqrt{(\pi^2j^2/4L^2 + e)} - \pi^2j/L^2$$

Stress due to this

$$= \frac{D_oE}{2R} = \frac{D_oE}{2}\left[\frac{2\pi}{L}\sqrt{(\pi^2j^2/4L^2 + e)} - \pi^2j/L^2\right]$$

Equating this to $g$ gives $j = ED_oe/g - gL^2/\pi^2ED_o \quad . \quad (25)$

So $L$ required for given $j$ at elastic limit

$$= \pi ED_o\sqrt{(e - gj/ED_o)}/g \quad . \quad . \quad . \quad . \quad (26)$$

nd deflection after expansion, from eqns. (18) and (24) is

$$= L^2/\pi^2 R = \frac{L^2}{\pi^2}\frac{2\pi}{L}\sqrt{(\pi^2 j^2/4L^2 + e)} = \sqrt{(j^2 + 4L^2 e/\pi^2)} \quad . \quad (27)$$

or an expansion bend, the value of $e$ is, in effect, multiplied by $_p/L_b$, where $L_p$ is the pitch of the expansion bends and $L_b$ the ngth of the expansion bend, since the expansion of $L_p$ is taken p in $L_b$. Applying this factor to $e$ in (9) the equation becomes

$$g^2 L_b^3 + \pi^2 E g D_o j L_b = \pi^2 E^2 D_o^2 e L_p \quad . \quad . \quad . \quad (28)$$

hich is solved by trial.

And deflection after expansion, from eqn. (27), becomes

$$\sqrt{(j^2 + 4eL_pL_b/\pi^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

It is obvious that, for a strut with the ends held in alignment, ıe middle half may be treated as a strut with pivoted ends, the nd quarters being identical in form to the quarters adjoining, nd the total deflection is therefore twice the deflection of the iddle half. The above formulae may be applied direct to uminium-sheathed cable.

**6.5) Development of Formula for Support Spacing for Lead- or Alloy-Sheathed Cable**

The bending moment of the metallic components of the cable found as follows:

*Conductor*.—If there are $n$ wires of diameter $c$, the bending ıoment due to these will be

$$n\frac{\pi c^4}{64}\frac{E}{R}$$

s bending will be within the elastic limit. The increased length f wire due to stranding will slightly increase the flexibility, but eglect of this factor will tend to offset the bending moment due ɔ the non-metallic parts of the cable, which cannot well be llowed for.

The modulus $E$ has no definite value for soft copper. As ɔon as it commences to harden under cold-working, this value oes not differ appreciably from that of hard copper, 8 × 10⁶lb/in².

So, from eqn. (1), bending moment

$$= \frac{\pi n c^4}{64}\frac{18 \times 10^6 \times 2\sqrt{(105e)}}{L}$$

$$= 9\pi n c^4\sqrt{(105e)} \times 10^6/16L$$

*Wire Armour*.—Similarly for $m$ armour wires of diameter $a$, nd $E = 22 \times 10^6$, bending moment due to wire armour

$$= 11\pi m a^4\sqrt{(105e)} \times 10^6/16L$$

*Sheath*.—The limit of proportionality for lead is indefinite, ut probably less than 100lb/in², and $E$ is about $2{\cdot}5 \times 10^6$lb/in². xcept for a small region at the neutral plane, the whole sheath ill therefore normally be stressed beyond the elastic limit.

For lead and its alloys, stress varies with rate of strain, and om examination of stress/strain graphs it is found that the reep rate in percentage per hour may be expressed in the form $0^{As-B}$, where $s$ is the stress and $A$ and $B$ are constants.

Since the stress is not proportional to the strain or, therefore, ɔ the distance from the neutral plane, standard beam theory is ot applicable, and the bending moment must be specially etermined.

Consider first a solid cylinder, radius $r$, and assume a rate of eating equal to that required to raise to final temperature in hours at a uniform rate.

Strain at $x$ from neutral plane $= x/R$.
Rate of strain for above rate of heating $= 100/hR\%$ per hour
So stress at $x$ from neutral plane is given by

$$10^{As-B} = 100x/hR$$

or $As - B = \log 100x - \log hR$
logarithms being to base 10 unless otherwise indicated, so

$$s = (2 + B - \log hR + \log x)/A = \text{say } (F + \log x)/A.$$

Bending moment of solid cylinder

$$= 4\int_0^r sx\sqrt{(r^2 - x^2)}dx$$

$$= \frac{4}{A}\int_0^r x(F + \log x)\sqrt{(r^2 - x^2)}dx$$

$$= \frac{4F}{A}\int_0^r x\sqrt{(r^2 - x^2)}dx + \frac{4}{A}\int_0^r x\sqrt{(r^2 - x^2)}\log x\,dx$$

$$= \frac{4F}{A}\left[-\frac{1}{3}(r^2 - x^2)^{3/2}\right]_0^r + \frac{4}{A}0{\cdot}434\left[\frac{1}{3}(r^2 - x^2)^{3/2}\left(\frac{1}{3} - \log_\varepsilon x\right)\right.$$
$$\left. + \frac{r^2}{3}\sqrt{(r^2 - x^2)} - \frac{r^3}{6}\log_\varepsilon\frac{r + \sqrt{(r^2 - x^2)}}{r - \sqrt{(r^2 - x^2)}}\right]_0^r$$

$$= 4Fr^3/3A + 4r^3 \times 0{\cdot}434\,(\log_\varepsilon 2r - 4/3)/3A$$

$$= 4r^3(F + \log 2r - 0{\cdot}579)/3A$$

$$= 4r^3(2 + B - \log hR + \log 2r - 0{\cdot}579)/3A$$

$$= 4r^3(1{\cdot}421 + B - \log hR + \log 2r)/3A$$

So for a hollow cylinder of diameters $D_o$ and $D_i$

$$\text{Bending moment} = D_o^3(1{\cdot}421 + B - \log hR + \log D_o)/6A$$
$$- D_i^3(1{\cdot}421 + B - \log hR + \log D_i)/6A$$
$$= (D_o^3 - D_i^3)(1{\cdot}421 + B - \log hR)/6A + (D_o^3 \log D_o$$
$$- D_i^3 \log D_i)/6A \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

Now $D_o^3 - D_i^3 = 6D^2t$ very nearly.

So eqn. (31) becomes

$$D^2t(1{\cdot}421 + B - \log hR)/A + (D_o^3 \log D_o - D_i^3 \log D_i)/6\text{A}$$

which, substituting for $R$ from eqn. (13),

$$= D^2t[1{\cdot}421 + B - \log h - \log L + \log 2\sqrt{(105)} + \tfrac{1}{2}\log e]/A$$
$$+ (D_o^3 \log D_o - D_i^3 \log D_i)/6A$$
$$= D^2t(2{\cdot}733 + B + \tfrac{1}{2}\log e$$
$$- \log h - \log L)/\text{A} + (D_o^3 \log D_o - D_i^3 \log D_i)/6A \quad . \quad (32)$$

Then if weight per unit length $= w$, complete bending moment is $\dfrac{wL^2}{12} = \dfrac{\pi\sqrt{(105e)} \times 10^6}{16L}(9nc^4 + 11ma^4)$ + expression (32), or

$$L^3 - 12D^2tL[2{\cdot}733 + B + \tfrac{1}{2}\log e - \log h - \log L$$
$$+ (D_o^3 \log D_o - D_i^3 \log D_i)/6D^2t]/wA$$
$$= 12\pi\sqrt{(105e)}(9nc^4 + 11ma^4)10^6/16w$$
$$= 24{\cdot}2\sqrt{e}(9nc^4 + 11ma^4)10^6/w.$$

This may be written

$$L^3 - 12D^2tL[U + B - \log L + (D_o^3 \log D_o - D_i^3 \log D_i)/6D^2t]/wA = V(9nc^4 + 11ma^4)10^6/w \quad . \quad (33)$$

The appropriate values of $U$ and $V$ are given in Section 8.

### (16.6) Example of Aluminium-Sheathed-Cable Calculation

$0{\cdot}3\,\text{in}^2$ 3-core 11 kV screened cable, aluminium sheath $2{\cdot}08\,\text{in} \times 1{\cdot}86\,\text{in}$.

Take $E = 10^7\,\text{lb/in}^2$, and $g = 10^4\,\text{lb/in}^2$.

Moment of inertia, $I = 0{\cdot}332$, weight $= 0{\cdot}443\,\text{lb/in}$, sheath temperature rise $= 36{\cdot}9°\text{C}$, $e = 0{\cdot}000023 \times 36{\cdot}9 = 0{\cdot}00085$.

*Beam Construction.*

Limiting value of $e$ for elastic accommodation of expansion, starting straight, from eqn. (16) is

$$8 \times 10^{12} \times 0{\cdot}332/35 \times 10^{14} \times 2{\cdot}08^3 \times 0{\cdot}443 = 0{\cdot}00019$$

Expansion, therefore, cannot be elastically accommodated from the straight position. Maximum length without exceeding yield stress, from eqn. (15)

$$= \sqrt{(24 \times 10^4 \times 0{\cdot}332/2{\cdot}08 \times 0{\cdot}443)} = 294\,\text{in} = 24\,\text{ft}\ \ 6\,\text{in}.$$

Initial deflection for elastic accommodation for 294 in spans, from eqn. (17),

$$= 315 \times 10^7 \times 0{\cdot}332 \times 0{\cdot}00085/4 \times 0{\cdot}443 \times 294^2 - 0{\cdot}443 \times 294^4/768 \times 10^7 \times 0{\cdot}332 = 5{\cdot}8 - 1{\cdot}3 = 4{\cdot}5\,\text{in}.$$

Similarly, for a span of 180 in the initial deflection required would be 15·5 in.

*Expansion Bend Construction.*

Pitch of bends = 50 yd = 1 800 in.

Assuming initial deflection of 3 in, the minimum length of expansion bend $L_b$ for elastic accommodation is found thus:

*Pivoted ends:* from eqn. (28),

$$10^8L_b^3 + \pi^2 \times 10^7 \times 10^4 \times 2{\cdot}08 \times 3L_b = \pi^2 \times 10^{14} \times 2{\cdot}08^2 \times 0{\cdot}00085 \times 1\,800$$

from which

$$L_b^3 + 61\,000Ls = 65\,000\,000$$

and $L_b = 352\,\text{in}$.

Deflection after expansion, from eqn. (29),

$$= \sqrt{(3^2 + 4 \times 0{\cdot}00085 \times 1\,800 \times 352/\pi^2)} = 15{\cdot}1$$

Thrust $= 10^7 \times 0{\cdot}332\pi^2/352^2 = 264\,\text{lb}$.

*Aligned ends.* Assuming the same total initial deflection o 3 in or 1·5 in, for a half-span,

$$10^8(L_b/2)^3 + \pi^2 \times 10^7 \times 10^4 \times 2{\cdot}08 \times 1{\cdot}5L_b/2 = \pi^2 \times 10^{14} \times 2{\cdot}08^2 \times 0{\cdot}00085 \times 1\,800$$

from which $L_b = 755\,\text{in}$.

Deflection after expansion

$$= 2\sqrt{(1{\cdot}5^2 + 4 \times 0{\cdot}00085 \times 1\,800 \times 377{\cdot}5/\pi^2)} = 30{\cdot}8\,\text{in}.$$

Thrust $= 10^7 \times 0{\cdot}332\pi^2/377{\cdot}5^2 = 230\,\text{lb}$.

Taking values two-thirds of the way from those for pivote ends to those for aligned ends gives a length of expansion ben of 621 in = 51 ft 9 in, deflection after expansion of 25·6 in, an thrust 241 lb. The length may if desired be reduced, with th consequence of an increased initial deflection.

Try $L_b = 20\,\text{ft} = 240\,\text{in}$. Effective value of $e = 0{\cdot}0008 \times 1\,000/240 = 0{\cdot}00638$.

*Pivoted ends:* initial deflection, from eqn. (25)

$$= 10^7 \times 2{\cdot}08 \times 0{\cdot}00638/10^4 - 10^4 \times 240^2/(10^7 \times 2{\cdot}08\pi^2) = 13{\cdot}3 - 2{\cdot}8 = 10{\cdot}5\,\text{in}$$

Deflection after expansion, from eqn. (27),

$$= \sqrt{(10{\cdot}5^2 + 4 \times 0{\cdot}00638 \times 240^2/\pi^2)} = 16{\cdot}1\,\text{in}.$$

Thrust $= 10^7 \times 0{\cdot}332\pi^2/240^2 = 568\,\text{lb}$.

*Aligned ends:* initial deflection

$$= 2[10^7 \times 2{\cdot}08 \times 0{\cdot}00638/10^4 - 10^4 \times 120^2/(10^7 \times 2{\cdot}08\pi^2)] = 25{\cdot}2\,\text{in}$$

Deflection after expansion

$$= 2\sqrt{(25{\cdot}2^2 + 4 \times 0{\cdot}00638 \times 120^2/\pi^2)} = 51{\cdot}9\,\text{in}$$

Thrust $= 10^7 \times 0{\cdot}332\pi^2/120^2 = 2\,272\,\text{lb}$.

Deriving the effective values in the same way gives an initia deflection of 20·3 in, deflection after expansion of 40·0 in, an thrust of 1 704 lb.

This suggests that to operate an expansion bend within th elastic limit involves inconveniently large dimensions.

*Strut Construction.*

Take 120 in span. Check that 3 in initial deflection is adequat thus:

Initial deflection required, from eqn. (25),

$$= 10^7 \times 2{\cdot}08 \times 0{\cdot}00085/10^4 - 10^4 \times 120^2/10^7 \times 2{\cdot}08\pi^2 = 1{\cdot}77 - 0{\cdot}70 = 1{\cdot}07\,\text{in}$$

This indicates that the 3 in initial deflection is more than i required for elastic accommodation, or alternatively that pro vision for the latter is unlikely to place any restriction on spa length.

Deflection after expansion, from eqn. (27),

$$= \sqrt{(3^2 + 4 \times 0{\cdot}00085 \times 120^2/\pi^2)} = 3{\cdot}08\,\text{in}.$$

## DISCUSSION BEFORE THE UTILIZATION SECTION, 14TH APRIL, 1955

**Mr. D. B. Hogg:** I do not suppose there is anybody in the country, except the railways, who has hundreds of miles of cables run on posts, but there are at least three other industries which have a few miles. I have seen quite a few miles of cables run under similar arrangements in steel-works, in oil-works and in the chemical industry.

In one factory, 48 miles of h.v. cable and 227 miles of various m.v. cables have been installed since 1934 and probably twice as much before that date. All the cables are lead-alloy sheathed and wire armoured. The h.v. cable cores are mostly of $0{\cdot}25\,\text{in}^2$ section and the m.v. cables are of various sizes, a large proportion being of $0{\cdot}4\,\text{in}^2$ core section. In another factory built since the war, 26 miles of various cables have been laid in the open. In no case has any evidence been found that the lead sheaths hav fractured and allowed compound to emerge. All the cables ar inspected regularly, and since the paper was received a ver special inspection has been made at various points which con firms that there is no knowledge of any trouble on these cables although the spacing averages between $3\frac{1}{2}$ and $4\frac{1}{2}$ ft.

It is rather puzzling to know why we have had no troubl compared with the large amount of trouble with cables on th railways, and I should like to ask the author whether his troubl can in any way be caused by vibration from passing trains. Th only case we can trace of cracked lead sheaths in these two factories was in 1930, when an unarmoured pure-lead-sheathed h.v. cable in a duct crossing a railway cracked and the researc

people suggested the cause was vibration. The cable was successfully replaced with one having an lead-alloy sheath. It should be stated that, in general, in these factories the loads are very steady and do not vary much from one part of the year to another or from night to day. Can it be that the low temperature and lack of sunshine on the north-east coast has contributed to our lack of breakdown?

**Mr. J. A. Broughall:** The railways have been mentioned a good deal as having serious trouble with sheath cracking. A great deal of thought has been given to the question, about which very divergent views are held.

After nearly 20 years of responsibility in this matter, I consider that the worst way to lay power and pilot cables is to put them on hooks. The policy of British Railways now is to bury cables wherever possible, and to give them continuous support in a concrete trough where they cannot be buried. Where neither is possible we put them on hooks with continuous support which acts as a sun shield. It is only in the last resort that we put them on hooks.

In some way or other we must have misled the author because I cannot agree with his conclusions. For instance, he states that 10% of the cables along the line are cracked. In fact, what puzzles us is that, of the cable laid which was suffering from cracks, only about 10% of the spans are in trouble. We showed the author as many cracks as possible, and I think that further statistical analysis would modify Table 1 and perhaps lead to different deductions. We have many miles of cable hung at the "wrong" spacing without cracks as well as with cracks.

There are two points on which I agree with the author. He states that lead is a peculiar metal and has no elastic limit or, at least, a very low one. I have been taught that it is not a solid at all but really only a sort of liquid. If this is so (I believe that lead roofs have to be replaced on cathedrals every hundred or so years because the lead has run away from the ridge), its random behaviour is probably explained.

I have also been taught that if you get a complicated formula it is probably wrong! I wonder whether the author, in developing his formula, has regarded lead as being more stable than he originally intended to do. In my view his conclusions must be accepted with very great reserve.

**Mr. J. V. Peacock:** The paper has a general title, although it is based on extreme cases, and I think we must bear in mind that the author's conclusions—assuming they are right—need not be applied with precision where conditions are less onerous.

In industrial situations this trouble is not general; long runs of cable are either underground or inside buildings, where the range of ambient temperature is restricted, and long runs are not often straight, so that outlets for expansion occur at changes of direction. Conductor sizes may be selected by voltage drop or fault conditions, thus restricting the working range of temperature.

To put the author's conclusions into practice, I suggest that more information is needed. In the first place, an estimate of the expansion of the cable must be made, which involves the coefficient of thermal expansion. Only two tests are recorded in the paper, both on 3-core cables, and it would be useful to make other tests, ranging from single-core cables with a large ratio of copper to lead, down to pilot cables with many cores having a much smaller ratio. Between these limits it should be possible to select a value for any cable normally used.

The second point relates to the initial sag, for which the author recommends 2%. Clearly this should be related to the ambient temperature when laying, and it seems that graphs or Tables, as for overhead lines, are needed to fix the initial sag at any temperature likely to be encountered, and based, presumably, on 2% sag at the lowest probable temperature.

Aluminium-sheathed cables present a different case, because all the metallic elements are elastic. The author's calculations for lead are based on creep due to repeated cyclic changes, but with aluminium, if the limits are exceeded, we can expect failure the first time instead of after ten years or so.

Of the three methods of laying mentioned by the author, I feel that beam construction is bound to be untidy, at all events where there is a mixed run of cables having different sags, and I do not entirely agree with the author's assertion that tidiness must give way to correct engineering, for I think it is possible to have both, by using the expansion-bend construction.

I am puzzled by the conclusion that spans for strut construction should be less than one-third of those for beam construction, because there seems little difference in method from the practical standpoint. Setting the initial deflection in opposite directions in alternate spans implies, I think, that the cable must not be restrained, except axially, at the cleats, and since the slope of the cable at the points of support will need to vary with temperature, it seems that the cleats must be freely pivoted. Is that the intention?

**Mr. C. C. Barnes:** Some years ago when writing a book* on electric cables I made a review of information relating to cables installed on cleats, racks and hangers. Unfortunately, however, the data obtained were limited and appeared to be very arbitrary. For example, one practice used for power-station work was based on racks spaced at intervals of not more than 3 ft for cables of 1 in external diameter and over, and not more than 2 ft for cables less than 1 in external diameter. The author, however, states that a simple relationship between spacing, dimensions and weight is not possible.

Furthermore, in the 19 installations examined and recorded in Table 1, the actual spacings used are greater than 3 ft in every case and the two most successful installations shown have a support spacing of 8 ft. The author's conclusion that the incidence of sheath fracture with lead- and alloy-sheathed cables run on spaced supports is generally due to the support spacing being too short is an important recommendation. I believe, however, that there must be many installations with considerably smaller spacings than those recommended in the paper, and they may justify careful examination. Can the author indicate the extent to which cables to-day are installed outdoors on spaced supports?

The problem discussed is very important, because recently cables for up to 6·6 kV working have been permitted an extra 10° C temperature rise (i.e. 80° C maximum conductor temperature), and it is hoped that this higher conductor temperature will in due course also be applicable to 11 kV cables. This means that troubles experienced with badly installed cables may tend to increase if advantage is taken of the higher current loadings. In Section 1 the statement is made that a material portion of lead-sheathed power cables installed out of doors above ground in this country has developed sheath fracture. Could the author state the number of faults experienced per year per 100 miles of cable installed in this manner? It is also stated that following sheath fracture, cases of cable failure due to this fault are rare, as the discharge of compound prevents the entry of moisture. With pre-impregnated cables, however, there is no free compound. Do pre-impregnated cables exhibit a greater failure rate than mass-impregnated cables when installed on spaced supports?

In general, all cables installed on spaced supports are in the voltage range 1·1–33 kV and design details for these cables are given in B.S. 480: 1954. It would be very helpful if the author would expand Table 5 (or add curves) to give calculated spans for the range of conductor sizes and voltages given in B.S. 480: 1954.

* Barnes, C. C.: "Power Cables: their Design and Installation" (Chapman and Hall, London, 1953).

In Section 12 alloy E is recommended as the most suitable lead alloy to stand up to slow repeated bending beyond its elastic limit. The need is emphasized, however, for further research and I should like to know whether this is being done by cable makers.

I regret the author has not provided any references to other published data. P. E. Williams* gave a very interesting and useful résumé of existing installation practice for railway work in 1947.

The conclusions recorded in Section 9.1 are valuable, particularly if confirmed by service experience. Are the guiding rules quoted used by the company with which the author is associated and also by the other seven cable makers referred to earlier?

**Mr. W. J. Webb:** We should accept with caution the view that cable supported intermittently may be an even better arrangement than continuous support. Engineering instinct leads one to regard continuous support as the best method of avoiding fracture of the supported member, and it is therefore somewhat surprising to find the author proposing a spacing which is appreciably greater than that normally used, which has been arrived at empirically after many years of practical experience.

The paper gives very little service evidence supporting the conclusions theoretically deduced by the author, and I should have liked to see in Table 1 several more examples of installations having spans in accordance with the author's theory. Furthermore, Table 1 does not indicate the extent of the installations from which the examples are quoted. It is worth noting that the instance quoted in the Introduction may be reworded to read that 90% of the drum lengths of cable more than ten years old were sound, which I suggest is quite a fair picture.

The continuous support of cables usually involves the use of cable troughing. Does not the author consider that the sun shielding provided by this arrangement is of some advantage in avoiding stress variation due to uneven heating?

Having regard to the peculiar behaviour of lead and its alloys as structural materials, it would have been expected that vibration would have merited more consideration than the brief reference made to it in the paper.

Since increased support spacing would increase the mechanical tension in the cable, what is the author's view of the possible effect on the life of the cable joints? Finally, I think that possible effects of the nature of the terrain should not be overlooked.

**Mr. E. A. Cullen:** For very many years I was interested in a group of feeder cables which were supported on metal hangers spaced at intervals of 3 ft. The cable route was along a railway viaduct running some 1 500 yd north–south, and faced west, so the full effect of sunlight was cause for concern. Maximum current loadings prevailed for long periods throughout the day and generally ideal conditions for thermal stressing existed. Three of the cables laid about 1912 were 0·15 in 3-core belted-type lead-sheathed steel-wire armoured; another 0·25 in 3-core cable followed in about 1926. Cable lengths were of the order of 300 yd and particularly short small-diameter cast-iron joints solidly compounded were used. Hangers were fixed to the viaduct track walls, the cable at places being within 36 in of the track in the vertical plane at a height of 30 in from the ballast. Over the main bridge the height was increased to some 15 ft. Main-line fast traffic is very heavy. Bridge movement, general vibration, plus thermal stressing due to load and ambients might well have caused excessive flexing and metal fatigue, but in a 25-year association no evidence of this was forthcoming.

Naturally I am reluctant to accept the author's conclusion on shorter spacing, and I suggest that more consideration might well be given to cable make-up when this method of installing cable is to be used.

British Standards to-day permit a lesser dimension in sheath and insulation thicknesses with possibly tighter laying of the cores, and it seems to me the older cables provided the better medium for internal movement and expansion without the danger of introducing excessive sheath stressing.

Reference is made to the use of single-lead type of cable, which appears to be more prone to fracture because of the higher internal pressures which apply on this kind of cable when thermally stressed. Armouring also plays an important part, and I suggest that because of the mechanical stressing it might be worth while extending the use of tape armouring in construction work of this kind.

Greater use of aluminium-sheathed cables has been suggested because of the increased spacing permissible; here there is a need to use bolted cleats, which should be avoided. If manufacturers provided a less rigid cable which would lie more naturally on supports the use of such cleats would not be necessary.

Nothing has been said about the form of extrusion which should be applied to lead-sheathed cables carried on supports. I believe weaknesses inherent in hydraulically extruded sheathing are contributory factors to breakdown.

More recently I have been responsible for the operation of some 25 miles of 33 kV h.s.l. and H-type cable. This is divided into feeder sections with maximum and minimum lengths of 5·7 and 1·5 miles, and cable sizes vary between 0·3 and 0·1 in$^2$ and have three cores. Support posts are consistent at 6 ft spacings, sagging is regular and no distortion is visible, although feeder loading and ambients coincide and can be excessive at times.

In contrast, a length of 0·1 in$^2$ 3-core 33 kV aluminium-sheathed cable on supports at 15 ft intervals has an unnatural appearance of tenseness and rigidity. When fully loaded and subject to stressing I have a feeling it might be prone to fracture.

Finally, I would refer to several installations of heavy power cables where catenary supporting has been effectively applied; 30–40 ft spans were general and pigskin straps at 2 ft intervals carried the cables. Maintenance was unusually low, and the freedom of movement provided by this form of construction to heavily loaded 33 and 6 kV 3-core belted-type feeders paid handsome dividends. I never experienced any major troubles with these cables over a period of 20 years.

**Mr. T. S. Pick:** On London Transport a large proportion of our h.v. cable is now reaching 50 years of life. On some 500 miles of original cable on the Underground Railway, during the first 20 years we averaged less than three failures a year. In 1934 we took over the Metropolitan Railway, and I was interested to find that we had a number of cracks in the lead. These arose from installations on posts, made in the middle 1920's, of mass-impregnated cables with pure-lead sheathing, armoured and served. Much of this cable has been replaced after a service life of only 25 years.

Our real trouble started when we reduced the dimensions of the cables, particularly those to B.S. 480: 1954. This resulted in a considerable decline in the mechanical properties, which are an important factor in post-run installation. The original cable on the Underground had a very heavy sheath, 98% lead plus 2% tin, whereas the B.S. 480 cable had a much lighter sheath of C-alloy. It seems that the original cables acted as a beam with nice curves on top, whereas the smaller cables act rather like pieces of string, forming catenaries with relatively sharp bends.

The post spacing on the London Transport system is closer than the author recommends, it being determined by the necessity of providing a common-purpose run for the e.h.v. cables, traction

* Williams, P. E.: "Power Cables on Brackets," *Electrical Review*, 1947, 140, p. 1063.

cables, signal and communication cables and air pipes. We overcome the problem of expansion of the e.h.v. cables by using a proportion of flat shelf brackets to enable the cables to move laterally at many points, to prevent cumulative longitudinal movement.

We would not replace our post runs. Our intensive service limits the access time available for maintenance; post runs enable us to accommodate the large number of cables involved in the very limited cross-sectional area of track formation width available, while providing ready access for inspection and repair.

The author has drawn a number of conclusions from measurements. Railway cables are subjected to sustained overloads and fault conditions. I have had experience of an 11 kV cable being lifted out of its bracket at many points under fault conditions, and it seems that in this case measurements made after its replacement would be of little value in an analysis of bracket spacing.

**Mr. H. Elder:** Our tendency in New Zealand at the present time is to bury 11 kV a.c. and 1 500 volt d.c. cables. This is partly due to the fact that troubles in the past have occurred through laying cables on concrete supports alongside the tracks. During track duplication it was necessary to move the cable line, and sheath cracking set in at the points which had been kinked over the supporting insulators.

Does the theory outlined in the paper apply to a cable which may subsequently have to be re-routed?

Could any of the failures observed by the author be attributed to electrolysis by stray direct earth currents?

**Mr. G. Davidson:** In order to be in a position to judge the apparent discrepancies between the author's experience and that of other speakers we should be given the relationships between the loadings and rated capacities of the cables—their maximum and average currents and the cyclic variations in each case.

The new practice of British Railways is to carry cables in continuous flat concrete troughs, the trough covers protecting the cables from sunlight; but unless it reduces the thermal effects sufficiently, this practice may be more troublesome than carrying them on supports at regular intervals, because with a cable laid flat any expansion between long straight lengths could cause short S-bends sideways, which would be worse than if the cables had regular sags between supports.

**Mr. W. S. Lovely:** I have had considerable experience with cable work in the field, and not having heard of any wholesale failure was alarmed by the impression that there had been a considerable number of failures throughout all the cable in service. However, it seems that the figure of 10% which is mentioned is not quite what it appears to be.

I believe that either continuous support allowing horizontal freedom or closely placed cleats actually gripping the cable are correct for plain lead-sheathed cable. For armoured cable, which I would elect to use whenever possible for cables racked above ground, I consider that the use of wide hook-type brackets spaced at such intervals as result in reasonable sag is good practice. When continuous supporting has been used it has been partly as an economy, because such an arrangement permits the reduction of the number of supports, with consequent saving in cost. At the same time I feel that continuous support is a useful thing to have, together with positions arranged at intervals where the total expansion of a length of cable can be accommodated. Such an expansion loop should be preset in the direction in which further movement is required.

So far as the actual spacing of supports is concerned, I think that in the early days positioning of the cleats was as much associated with the controlling of single-core cables under short-circuit conditions as with actual support, and this led to the $2\frac{1}{2}$–3 ft spacing to which we are accustomed. When these spacings are increased it will be necessary to provide additional control for single-core cables, but this can be done and does not necessitate the close spacing of supports. However, the more you increase the spacing the more you will invite sagging. Cable is a tube, either a large-diameter strong tube or a small-diameter weak one, and such a tube will have a deflection under its own weight. I cannot understand the author's suggestion about lining up the sag with the expansion; I believe that the two will still be additive, and that anything done mechanically will be increased by thermal conditions. Obviously, on the tube analogy, a steel-wire-armoured cable has a better chance of remaining straight with widely spaced supports than has non-armoured cable.

What I consider is very important is that supports should be wide—say 2–3 in—with close spacing of cleats, and even 4 in with open spacing.

**Mr. W. G. Hawley:** The best place to put a cable is underground, where it is at least shielded from the sun, where there is some scope for distributed movement all along its length, and where even if sheath leakage were to occur it would not be noticed. The temperature of cables above the ground can be increased above ambient both by solar radiation and by current loading. As a consequence there will be thermal expansion of exposed cables in a longitudinal sense, so that some care has to be taken to install them correctly, or immense pressure will be brought to bear somewhere, probably at joint positions.

I endorse the method advocated by the author. I have found that if a cable, clamped firmly at one end, is supported on brackets not far enough apart, the cable moves outwards over the brackets upon heating, and fails to return completely to its original position when it cools. On the other hand, if the brackets are too far apart, the cable when first heated accommodates itself more closely in the several spans, and again fails to revert to its original position upon cooling. There is therefore a best spacing of the supports (not too critical) at which expansion and contraction of the cable take place in the several individual spans.

Fig. 3 shows an installation which is obviously clamped at the two ends, and if the supports are too close together the cables will push away from those ends and collapse will occur in one of the middle spans of the installation, as illustrated.

Remarks made by previous speakers suggest that satisfactory operation is obtainable with cables laid straight on supports spaced relatively close together. The L.T.E., for instance, like their cables to appear straight and hence neat when viewed from trains running alongside. Since thermal expansion has to be taken up somehow, this is (it seems unknowingly) catered for by the frequent use of long shelf brackets, so as to give the cables lateral play. Cables laid in troughs and on sleepers likewise behave well, because of free side-play. These methods are to be recommended, of course, where there is a prejudice against festooning.

The worst way of trying to solve the problem is to provide for expansion and contraction at a few selected spots, or expansion gaps, for in time large amounts of "spare" cable are forced into these gaps, where subsequent up-and-down movement quickly causes fatigue fracture of the lead sheath.

**Mr. C. A. Craig** (*communicated*): It is significant that the author has not listed in Table 1 a single installation with posts spaced some 4–$5\frac{1}{2}$ ft apart in which the condition of the sheathing or the behaviour of the cables has been found to be satisfactory. While I agree that there has been a heavy incidence of sheath failure among cables supported on posts with this order of spacing, I believe that the Table is hardly representative of actual conditions on site. Furthermore, the author lists only three cases of posts spaced 6 ft or more apart, and in each the condition of

the sheathing and the behaviour of the cables are satisfactory. Presumably the few installations listed as employing the wider spacing of posts is due to the scarcity of such installations. Perhaps the author would expand this Section of the paper and say whether he found any satisfactory installations with the closer spacing of posts or unsatisfactory installations with the wider spacing.

It is generally accepted that the best place for a cable is buried direct in the ground, and it is evident that the author shares this view. However, this is not always possible with certain installations, particularly where cables are laid beside a railway. Such cable routes must of necessity be heterogeneous in type. Since intermittent support with an infinite number of supports is virtually the same as continuous support, it would seem that there is a case for short spans, having due regard to economic limits; yet the author, while accepting continuous support as good practice, recommends the use of spans longer than those usually adopted when intermittent support is to be provided.

While the adoption of wider spans for cable supports would be advantageous to users, since it should tend to reduce prime costs, no doubt the user will require definite assurances based on practical experience in the field or on the results of accelerated laboratory tests that the adoption of wider spans will prove the recommendations made by the author. On the one hand, experience in the field must of necessity extend over a long period, and on the other, accelerated laboratory tests may prove difficult to achieve; however, it is to be hoped that cable makers will endeavour to prove the case for spans wider than those generally adopted at present.

I should like more information on the choice of lead alloys for cables to be installed with intermittent support.

The author appears to have confined his investigations to solid-type cables, and it would be interesting to have his views on intermittent support for gas-pressure, oil-filled and dry-core air-spaced telephone armoured and unarmoured cables.

In Section 14 the author recommends that the cable should be clamped at each support, and offset up and down in alternate spans by hooks midway between supports. This offset would be extremely unsightly in exposed positions, and virtually impracticable so far as a post route is concerned.

## THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

**Mr. W. Holttum** (*in reply*): The main issue of the paper is fundamentally simple, and its reception shows the usual reluctance to accept an unaccustomed idea which is contrary to common practice. A logical explanation is given (Section 4) for the fact that a large amount of sheath fracture has occurred in cables with short support spacing, and satisfactory behaviour has been found in the small number of installations which could be found with long support spacing. It is notable that none of those who hesitate to accept the conclusions of the paper has attempted to show that this explanation is unsound. The choice is between cable suffering severe stresses and irregular bending, as occurs with continuous support or short-spaced intermittent support, and cable on wide-spaced supports, the stresses being relieved by regularly distributed bending.

Several speakers have referred to the absence of trouble with a large quantity of cable installed on supports at spacings much less than recommended in the paper. The reason is that sheath fracture depends upon temperature cycles as well as support spacing, and will occur only if the temperature cycles are of sufficient range and frequency. The combinations of values which would be dangerous cannot be defined, but localized bending would be observable before fracture develops.

There are so many variants in both installation and operation that it may not be possible to account for the behaviour in any particular case, even after inspection. Trouble-free behaviour with short support spacing is no indication that longer spacing would not be preferable. In addition to economy, it will conduce to even longer life.

Reference has been made to the possibility of vibration being a contributory factor. While this occurs to some extent on railway routes and in power-station tunnels, there appears to be no criterion of harmful severity. Where vibration is present it is impossible to say whether it may have accelerated sheath fracture, for the fractures observed were mostly so clearly associated with the mechanism described that vibration effects, if any, can be only a very minor factor. The same applies to methods of extrusion, and the fractures are not associated with electrolysis. The unimportance of vibration is supported by the first case referred to by Mr. Cullen.

In reply to Mr. Broughall and Mr. Webb, the service record quoted verbatim in the Introduction clearly implies that a serious amount of sheath fracture has occurred. Table 1 is a record of fact, and no amount of trouble-free cable can detract from the conclusions to which it leads.

I regret to learn that the policy of British Railways is to bury cables where possible, and otherwise to give them continuous support. Installation on hooks is the most economical method, and a strong case can be made out for this being technically preferable to any other.

One or two speakers criticized the complication of the formula for determining support spacing. The calculation is much simpler than that to determine current-carrying capacity.

The spacing for the aluminium-sheathed cable referred to by Mr. Cullen is evidently too short. The satisfactory behaviour he reports of catenary-supported cables is interesting, and is doubtless accounted for by the expansion and contraction of the supporting catenary providing accommodation for the cable.

Mr. Peacock will no doubt agree that, whether conditions are onerous or not, the best method should be used, especially since it leads to economy. The amount of expansion is not critical, and in the relevant range has little effect on minimum spacing (see Table 4). The initial sag also is not critical, and increase beyond 2% will be beneficial provided that bending is not too severe. The reason that spans for strut construction can be much shorter than for beam construction is that in the latter case there are two points of inflection per span, but in the former only one, thus allowing continuous bending in each span. The cleats should be set in line with the cable or preferably be free to tilt.

In reply to Mr. Barnes, I have no information regarding the extent of new work of this kind, except that British Railways, who have the largest amount of cable installed in this way, no longer favour it. The recent increase of permissible operating temperature will tend to aggravate expansion trouble and make the methods advocated more necessary. No information is available regarding fault incidence. Since pre-impregnated cable will not discharge compound, undiscovered fractures no doubt exist and breakdown through entry of moisture is likely to occur earlier, but no data are available. There would be no point in extending Table 5 until some agreement is reached in the industry. Alloy E is recommended as suitable, but there is no information yet that it is the best. Research regarding the most suitable alloy is in hand in the C.M.A. and B.N.F.M.R.A. No references were given since I did not know of any, but the article by Mr. P. E.

Williams is an interesting contribution. The recommendations of the paper have not yet been adopted in the industry.

In further reply to Mr. Webb, shielding provided by troughing is beneficial provided that it reduces the maximum temperature, but this is offset by the disadvantage of continuous support, which results in irregular bending. Long support spacing relieves longitudinal stresses and should therefore be beneficial to joints.

Mr. Pick has evidently had an amount of useful experience, but without much more detailed information it is not possible to fit it into the picture. I am glad to see, however, that he is still favourable to post runs, one of their many advantages being accessibility for maintenance.

In reply to Mr. Elder, re-routing of cables on hooks is not to be recommended, since sheath fracture may occur through reverse bending of the supported regions, but provided that a limited number of fractures can be accepted and dealt with, such procedure is justifiable, and the calculated spacing will apply.

Mr. Davidson's remarks support the contention that installation on hooks is preferable to continuous support.

In reply to Mr. Lovely, accommodation of expansion at intervals has been tried, as reported in Section 6.

In reply to Mr. Craig, continuous support should not be confused with complete lateral restraint, which is necessary to make continuous support satisfactory, but movement at the ends may be difficult to control. There is no reason why installation on hooks should not be applied to gas-pressure, oil-filled and air-spaced telephone cables.

# DISCUSSION ON "DEVELOPMENT AND UTILIZATION OF HYDRO-ELECTRIC POWER IN UGANDA"*

## NORTH-WESTERN CENTRE, AT MANCHESTER, 4TH JANUARY, 1955

**Mr. J. F. Dunn:** I was interested to note that the water-soluble-salts method of impregnating wood poles has been found to be unsuccessful in Uganda, and that a good deal of trouble has been experienced from rot and termites. I note that creosoted poles only are now being used and that these are all from local-grown *Eucalyptus Saligna* trees. What degree of inspection has been applied to these? For example, are the trees selected in the forest in a similar way to that always, I think, adopted with poles ordered for use in this country from Scandinavia and other parts of the world? What precautions are taken as regards correct felling time and seasoning? Are the poles then individually inspected for defects after bark removal but before creosoting, and again afterwards to check the impregnation? How do these poles compare physically and in strength with the fir and larch poles to which we are more accustomed in this country?

It has long been demonstrated here and elsewhere that all these stages at least are highly important if trouble-free poles are to be obtained, and in view of the use of local-grown poles it would be interesting to know whether their quantity is sufficient to warrant the employment of specialized inspection personnel, since it has been amply demonstrated in this country that a thoroughly experienced approach is necessary in this direction.

**Mr. A. H. Gray:** In view of the prospects of long transmission lines, the authors decided to employ a system with a high rate of response. Will they indicate the actual rate of response achieved and its effect in practice on the under-excited zone of operation, and, furthermore, the transient performance they obtained during throwing load on and off the machine?

I was particularly interested in the novel method of obtaining this high rate of response on the excitation system, namely an electronic regulator feeding a rotary amplifier and an amplidyne, which in turn controls a buck-boost generator connected in the a.c. generator main field circuit. Such a system is definitely capable of giving quick response, but it does seem unnecessarily bulky and hence somewhat costly.

I am associated with the design of a more conventional static regulator which is capable of giving a similar performance with less equipment. This consists of a magnetic-amplifier regulator feeding a rotary amplifier, which in turn controls a buck-boost generator in the main exciter field circuit. Although the servo problem is more involved, it does not present any serious difficulty. A number of these sets have been built and tested for 75 mVA water-wheel sets and certain synchronous condensers, and these are at present being erected in Europe. Many more sets are now in the course of manufacture for machines both in this country and in the colonies. Apart from the reduction in the size of the buck-boost generator, the use of the magnetic amplifier involves no expendable units and is, I suggest, a further advantage of the conventional type of regulator.

The provision of a constant-output exciter to provide power to drive the buck-boost generator, and also to provide a.c. power to the governor pendulum motor and electronic regulator, is again a novel feature. The introduction of brush-gear in the pendulum-motor circuit is contrary to normal practice and must have aroused some doubt in the minds of the operating engineer. It seems to me that the small permanent-magnet generator allocated for this purpose possesses some advantage from the aspect of reliability.

The drive of the buck-boost generator in the conventional

* STOCK, J. M., and LITHGOW, J. C.: Paper No. 1658, May, 1954 (see 101, Part I, p. 373).

form of regulator has generally been an a.c. motor fitted with a flywheel to obviate any difficulties due to intermittent interruptions. Such a method is, I suggest, quite suitable.

It would appear from the paper that both the amplidyne and buck-boost generators are required for automatic and manual control. If this is correct it would appear that the large machine must be shut down if a failure should occur on either of the small sets. It is usual to provide hand control on the large set which is completely independent of the small sets.

Finally, has it been found necessary to include any protective limits on this equipment? Excitation systems with a high degree of forcing frequently need high- and low-limit excitation circuits to prevent exciter flashovers and loss of synchronism due to low excitation.

Why has this particular system of excitation been preferred to the more conventional type, which would appear to give similar characteristics?

**Mr. J. H. Aylward:** The authors state that the exciter is an enclosed machine taking its cooling air from the generator air circuit. Has it been found necessary to provide filters in the return air circuit? These have usually been provided where the exciters are enclosed-type machines and in most cases without recourse to an auxiliary fan.

The reduction in overall height of the set obtained by omitting the pilot exciter and governor generator is interesting. It is worth noting, however, that in most cases the station height is governed by the headroom required for lifting the generator rotor or stator. From the clearance provided between the crane hook and the top of the combinator gear it would appear that this is the case here also. Can the authors confirm this? The omission of the pilot exciter and governor generator would then have no effect on station constructional costs. The saving in the cost of the machines themselves is to some extent offset by the cost of the extra complication introduced into the main exciter and by the larger type of buck-boost exciter required, because this is in series with the generator field.

It is noted that the machines are suitable for operating as synchronous condensers. Presumably some machines would operate under-excited as condensers, to compensate for the leading apparent power of the line when the system is lightly loaded. It is difficult to envisage any other system condition under which synchronous-condenser operation is required, even when the contemplated system extensions have been completed. Is the decision to provide for synchronous condenser justified economically, and under what system conditions is this required?

From Fig. 4 it is noted that the complete bearing bracket is not removable through the stator bore and would have to be dismantled should it be necessary to remove the turbine runner upwards. Presumably a hatch will have been provided on the turbine-floor level and provision made for handling the turbine runner at this level with the main station crane.

The generator thrust collar shown in Fig. 4 is of most unusual design, being integral with the generator shaft. Normally these are separate items, the collar being pressed or shrunk on to the shaft. The more conventional arrangement would have helped from the transport point of view.

**Mr. G. M. Hardman:** In Section 4.3 the authors err by saying that the variable-pitch propeller turbine was selected because of the better efficiency characteristics of the propeller runner under variable heads. Surely the propeller type was chosen to give higher speed and lower cost, and then the variable-pitch propeller selected to give sustained efficiency at various loads and heads?

No mention is made of provision for pressure relief, either in the shape of surge tower or relief valve. Is this not necessary?

**Mr. I. F. Hay:** Has the electrical load developed in any particular direction? What is the demand of the average industrial consumer, and has it been possible to develop the potential load of the copper mining? Is it proposed to electrify any part of the railway system?

We learn of very large sums of money being spent in Uganda. What has been the effect upon the cost of living and the African population?

I was much impressed by the integrity of the British in every service in Uganda. Can it now be said that the Asian and strictly non-native element in the country is adopting a similar unselfish attitude?

**Mr. G. E. Woodhead** also contributed to the discussion at Manchester.

**Messrs. J. M. Stock** and **J. C. Lithgow** (*in reply*): In reply to Mr. Gray, it was appreciated during the design stage for Owen Falls that the station would probably be interconnected with long transmission lines, requiring voltage regulators having a high rate of response. At that time, however, the only type of regulator available from British manufacturers was the electronic type adopted, and this has given satisfactory service. Regulators with a high response rate similar to those described by Mr. Gray were available from Continental manufacturers, but have only since been developed in this country. The arrangement of the pendulum-motor supply is admittedly unusual, but has not led to operational difficulties.

In reply to Mr. Aylward, air filters are provided in the return air circuit and an auxiliary fan circulates air to the main exciter. The clearance between crane hook and top of stator is sufficient for all major components to be lifted over the stator and along the downstream side of the turbine house clear of the combinator. The stators are assembled on the main floor between the units. The runner blades can be removed through removable segments of the runner chamber, shown in Figs. 2 and 3; thus maintenance of the runner hub seals, bearing rings and trunnion blocks can be carried out *in situ*, and the need to remove the runner hub is therefore considerably reduced. The crane has access to the transverse galleries for blade removal, and suspension tackle is supplied for handling the blade from the hub to the longitudinal gallery. Transport of the generator shaft and thrust collar did not present difficulty, as the thrust bearing ring is removable and was transported separately.

Mr. Hardman is correct in his statement regarding the choice of variable-pitch propeller runners. Pressure relief valves and surge chambers are unnecessary in view of the short length of penstock.

In reply to Mr. Dunn, there are no seasons in Uganda and tree felling is carried out throughout the year. Detailed inspection, by a European employed full time on supervision of the Board's pole yard, is made of every pole before acceptance. The poles are seasoned for twelve months before impregnation; control of impregnation is by weight. The South African Bureau of Standards specifies a maximum strength modulus of 8 000 lb/in$^2$ for *Eucalyptus Saligna*, which compares favourably with 7 800 lb/in$^2$ for red fir. Since Uganda trees are quick-growing and have a smaller proportion of heart wood than South African trees, a modulus of 5 000 lb/in$^2$ has been adopted.

In reply to Mr. Hay, the electrical load has not yet developed in any particular direction. In 1954 there were 109 industrial consumers, each taking an average of 280 MWh/annum; a large textile mill with electrode boilers and a copper smelter are now being built near Owen Falls. Electrification of the railway is a question for consideration by the railway administration. The cost of living and the African population have not yet been greatly affected by the considerable amount of capital invested, since most of the labour, both African and non-African, employed on the capital projects is imported and is housed and fed by the employers.

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# AUTOMATIC CIRCUIT RECLOSERS

By G. F. PEIRSON, Member, A. H. POLLARD, B.Sc., Associate Member, and N. CARE, Member.

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## SUMMARY

Of recent years there has been a large increase in the use and application of electricity in rural areas. The loads are usually small but are distributed over very large areas, and a high standard of service is an essential requirement as prolonged interruption of supply may cause serious inconvenience to users.

Supplies in such areas are generally provided by high-voltage overhead lines, from which distribution transformers provide links with the general medium-voltage distribution networks. The transformers and spur h.v. lines are usually protected by fuses, with the number of h.v. circuit-breakers kept to a minimum. Under these conditions, therefore, h.v. faults of both a transient and a permanent nature might cause prolonged interruption of supply, owing to the distances to be covered before fuses can be replaced or circuit-breakers reclosed.

Where only a limited breaking capacity is required an automatic circuit recloser can be made to overcome the operational difficulties detailed above. The paper reviews some of the factors influencing the design, selection and application of circuit reclosers. The principles determining whether the main contacts of a recloser are to "lock open" or "hold closed" upon the completion of an operating sequence are discussed, and the co-ordination of reclosers with other reclosers and with fuses is described.

The development of the use of automatic-reclosing features is also discussed in relation to operation in conjunction with automatic sectionalizers.

## (1) INTRODUCTION

The greatest reliability in operation of a distribution system is achieved when measures are incorporated which are capable of counteracting the many hazards tending to interrupt the supply of electricity. Such hazards may cause persistent damage to plant or equipment and prevent the restoration of supply until the damaged equipment has been replaced. In many instances, however, lightning or other abnormal conditions merely cause flashovers on the overhead lines, and in these cases supplies can be restored without carrying out any replacement of the equipment concerned. For the purpose of the paper, faults causing persistent damage to equipment are referred to as "permanent faults" and those not causing persistent damage are referred to as "transient faults."

Electrical faults cannot be entirely eliminated, but their effects can be kept to a minimum by sectionalization. One method of sectionalization is by fuses, but this system may cause delay in restoring supply, as, on the blowing of a fuse due to either a transient or a permanent fault, the supply remains interrupted until some manual attention is given to the circuit. Statistics indicate that of the total number of faults occurring on h.v. overhead lines, 80% are of a temporary nature, i.e. the fault is cleared as soon as the lines are de-energized.

If a device can be fitted which will open when a fault occurs on a line and close as soon as the fault path is deionized, it follows that approximately 80% of the present interruptions of supply can be avoided, and only a flicker indicates that an operation has taken place.

Mr. Peirson is and Mr. Care was with the Midlands Electricity Board.
Mr. Pollard is with the British Thomson-Houston Co. Ltd.

Automatic reclosing mechanisms for fitting to oil circuit-breakers controlling h.v. lines have been available for some time, and devices called "automatic circuit reclosers" are now available for use on rural lines. These latter devices will be referred to as "reclosers."

## (2) OPERATIONAL REQUIREMENTS

Since the introduction of B.S. 1320 and the relaxed regulations applicable to 11-kV overhead lines up to $0 \cdot 05 \text{in}^2$ copper section, extensive use has been made of unearthed h.v. construction in rural areas.

Distribution transformers of the pole-mounting type have been installed in large numbers and have proved extremely reliable under service conditions. In an effort to minimize permanent interruptions to supply, the original policy of providing h.v. fuses on each distribution transformer has given way to the fuse protection of spur lines to which a number of pole transformers are solidly connected. Such h.v. distribution systems providing supplies in rural areas involve the use of long lengths of h.v. overhead lines which are of necessity exposed to widely varying atmospheric conditions. Abnormal atmospheric conditions, such as lightning storms or gales, may thus cause transient faults to occur due to flashovers, which it would not be economical to prevent by increasing air clearances or insulation levels.

Table 1 gives a summary of the types of faults which have occurred on systems of this nature, and Table 2 shows the outage times which often result from fuse operation on transient faults only. As will be seen, the majority of faults are of a transient nature, and if high-speed circuit interruption and reclosure could be provided to prevent transient faults causing fuses to operate, reduced outage times would result and the expensive running costs associated with fuse replacements would be minimized. The reclosers here described satisfactorily fulfil this requirement.

Conventional automatic-reclosing circuit-breakers of the weight-operated type have been available in this country for many years. They are designed to meet the requirements detailed above for dealing with transient faults, but have two principal disadvantages:

(*a*) The small number of operations obtainable before the weight has to be recharged.
(*b*) The tripping time of the breaker cannot be automatically varied.

This latter disadvantage means that, if a tripping time is selected to prevent subsidiary circuit fuses operating on the occurrence of transient faults, the circuit-breaker will automatically lock-out in the event of a permanent fault occurring, as the subsequent tripping time of the breaker cannot be delayed to permit the fuse on the subsidiary circuit to melt; thus the resultant interruption in supply cannot be automatically limited. The reclosers here described, however, are continuous in operation and have the characteristics of providing time-delay tripping in the event of a permanent fault occurring on the network; they thus permit normal fuse discrimination to operate and limit

### Table 1

SUMMARY OF INTERRUPTIONS ON RURAL H.V. LINES DURING THE YEAR ENDING DECEMBER, 1953

| Cause of interruption | Number of interruptions: Transient | Permanent | Total | Transient faults as percentage of total due to this cause |
|---|---|---|---|---|
| Lightning | 423 | 65 | 488 | 86·6 |
| Unknown | 193 | 0 | 193 | 100 |
| Birds mid-span | 80 | 6 | 86 | 93·0 |
| Birds at pole | 58 | 4 | 62 | 93·6 |
| Cables | 0 | 7 | 7 | 0 |
| Gales | 43 | 10 | 53 | 81·2 |
| Cattle rubbing | 32 | 3 | 35 | 91·4 |
| Insulators | 21 | 28 | 49 | 42·9 |
| Accident | 14 | 12 | 26 | 53·9 |
| Switchgear (s/station) | 0 | 2 | 2 | 0 |
| Vermin | 13 | 1 | 14 | 92·9 |
| Corrosion | 0 | 1 | 1 | 0 |
| Deterioration | 9 | 29 | 38 | 23·7 |
| Cable end-box (pole) | 0 | 3 | 3 | 0 |
| Trees | 6 | 1 | 7 | 85·8 |
| Conductors | 0 | 6 | 6 | 0 |
| Surge | 5 | 0 | 5 | 100 |
| Faulty manufacture | 0 | 2 | 2 | 0 |
| Malice | 5 | 13 | 18 | 27·8 |
| Sleet and ice | 5 | 3 | 8 | 62·5 |
| Line switch and fusegear | 4 | 12 | 16 | 25·0 |
| Faulty operation | 3 | 2 | 5 | 60·0 |
| Switchgear (pole) | 2 | 0 | 2 | 100 |
| Miscellaneous | 2 | 2 | 4 | 50·0 |
| Transformer (mains) | 2 | 26 | 28 | 7·2 |
| Binders, clamps and jumpers | 1 | 14 | 15 | 6·7 |
| Fault on consumers' apparatus | 1 | 0 | 1 | 100 |
| Ingress of moisture | 0 | 4 | 4 | 0 |
| Grand Totals | 922 | 256 | 1 178 | 78·2 |

### Table 2

OUTAGE TIMES RESULTING FROM FUSE OPERATION ON TRANSIENT FAULT CONDITIONS DURING YEAR ENDING DECEMBER, 1953

| Month | Number of interruptions in which fuses operated | Average time for fuse replacement h | min |
|---|---|---|---|
| January | 35 | 2 | — |
| February | 29 | 4 | 40 |
| March | 13 | 2 | 1 |
| April | 49 | 2 | 30 |
| May | 43 | 8 | 6 |
| June | 124 | 6 | 42 |
| July | 107 | 3 | 25 |
| August | 85 | 4 | — |
| September | 54 | 2 | — |
| October | 34 | 2 | — |
| November | 24 | 1 | 26 |
| December | 27 | 1 | 31 |
| Average fuse replacement time over the 12-month period—3h 22min | | | |

the interruption of supply to the short section of fuse-protected network on which the permanent fault has occurred.

#### (2.1) Method of Application

First, the requirement of a recloser is that it shall open with the minimum delay on the initial passage of the fault current. This means that a transient fault will be cleared with the least possible disturbance to the system and ensures that the recloser interrupts such transient faults without the fuse with which it co-ordinates suffering damage.

Secondly, provision must be made to prevent a transient fault from causing permanent interruption of supply, and this is obtained by means of the reclosing feature.

Thirdly, interruption of supply due to permanent faults must be limited as far as practicable, and this is obtained by utilizing a recloser in conjunction with other equipment.

#### (2.2) Recloser of the Lock-Open Type installed in the Main Supply Network with Subsidiary Lines Fuse-Protected, Fig. 1A

With this method all transient faults are cleared by the recloser, and in the event of a permanent fault developing, the

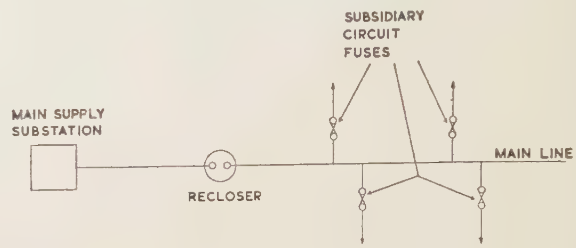



Fig. 1A.—Recloser of the lock-open type installed in the main supply network with subsidiary lines fuse-protected.

recloser in its normal sequence of operation automatically provides a time-delay trip which enables the fuse to operate only on the subsidiary circuit on which the permanent fault has occurred.

#### (2.3) Recloser of the Lock-Open Type installed in the Main Supply Network with Subsidiary Lines fitted with Sectionalizers, Fig. 1B

As in Section 2.2, all transient faults are dealt with by the recloser, and the passage of fault current through a "sectionalizer"

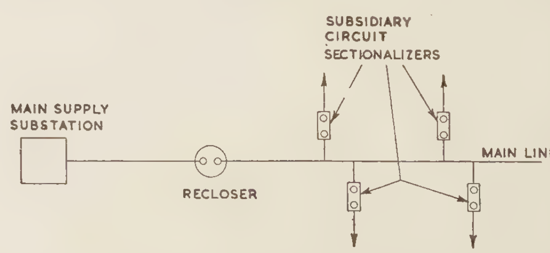



Fig. 1B.—Recloser of the lock-open type installed in the main supply network with subsidiary lines fitted with sectionalizers.

provides a means whereby a current-operated mechanism can automatically disconnect the faulty subsidiary circuit.

#### (2.4) Reclosers of the Hold-Closed Type installed in the Main Supply Network with Back-Up Fuse Protection and Subsidiary Circuits Fuse-Protected, Fig. 1C

As in Section 2.2, all transient faults are dealt with by the recloser and permanent faults on the subsidiary circuits by the fuses. In the event of a permanent fault developing in the portion of the main networks protected by the recloser, the recloser automatically holds closed and the back-up fuses operate.

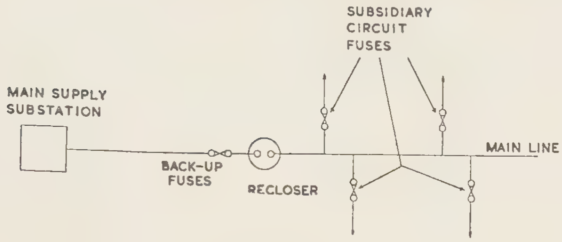



**Fig. 1c.**—Recloser of the hold-closed type installed in the main supply network with back-up fuse protection. Subsidiary circuits fuse-protected.

## (3) GENERAL DESCRIPTION OF CURRENT-OPERATED RECLOSERS

The recloser described in the paper consists of a normally closed oil circuit-breaker arranged for outdoor pole-mounting use. The breaker is held closed under the action of incorporated springs and is opened by the passage of a fault current (normally not less than twice full-load current) through a series solenoid. Movement of the solenoid plunger causes the recloser to open and interrupt the fault current. The plunger then returns to its original position under the action of a resetting spring, and, with reservations given later, the reclosing is automatic. Relay features are incorporated to control the reclosing and opening times, and a mechanism is provided to enable the recloser to lock open or hold closed at the end of its operating sequence as described below.

### (3.1) Reclosers of the Lock-Open Type

The design of the lock-open recloser described here provides for an operating cycle consisting of two high-speed trip operations followed by two time-delay trip operations, the basic time/travel curve being as shown in Fig. 2A.

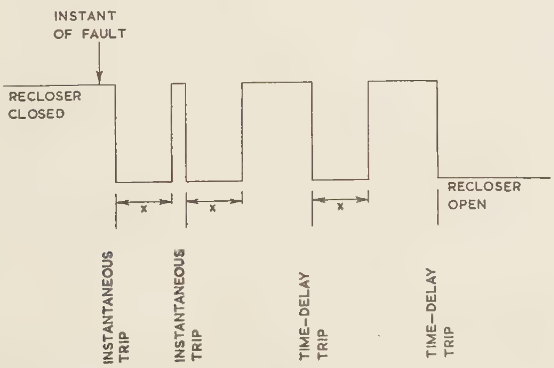



**Fig. 2A.**—Operating cycle of lock-open recloser.
Open-circuit time $x$ can be selected between the limits 0·25 and 1·0 sec.

The operation of the recloser is automatic, and if, owing to the non-persistence of the fault, operation is stopped at any time during the cycle shown in Fig. 2A, the mechanism is arranged to return to its normal position independent of the point in the operating cycle which has been reached.

The open-circuit time may be selected for given reclosers, and in certain designs of reclosers facilities are provided for the value to be varied between approximately 0·25 and 1 sec. The selection of the time interval to be adopted depends on operational requirements. The shortest interval may permit rotating machinery to coast through without the associated low-voltage release operating. This interval, however, may not give sufficient time for foreign bodies such as straw or branches of trees, initiating the fault, to fall clear and may cause a recloser to operate through to lock out; the advantages of maintaining supply under transient-fault conditions will then be lost.

In order to avoid deterioration of small fuses over as wide a range of fault current as possible, and to reduce the damage at the point of fault, the high-speed trip operations are made as fast as possible, with the actual operating time dependent upon the magnitude of the fault current and varying from $3\frac{1}{2}$ to $1\frac{1}{2}$ cycles.

The second high-speed trip operation is provided to permit clearance of faults caused by repetitive lightning strokes, and the further passage of fault current gives a second chance for foreign bodies to burn or fall clear. Fault statistics have indicated that approximately 75% of all faults are cleared on the first operation and a further 5% on the second high-speed operation.

The first time-delay trip operation is provided so that the passage of fault current is of sufficient duration to operate the fuses protecting the section of line on which the permanent fault has occurred; it is, on the other hand, not long enough to operate back-up over-current protection in the main supply system.

The second time-delay operation is provided as an extra safeguard where, owing to the limitation of fault current, accurate discrimination with fuses cannot be obtained on the first time-delay trip. Thus, the passage for a second time of the fault current may cause the protecting fuse to operate owing to pre-heating during the flow of the initial fault current, which otherwise would have resulted in the recloser locking open.

At the completion of the operating cycle the recloser automatically locks open. To provide for protection of 3-phase circuits, an interphase mechanical connection can generally be provided in order that when one recloser of the 3-phase group locks open the mechanical coupling trips and locks open the two other phases.

The recloser is normally fitted with a manually pole-operated lever which can be used to open the recloser or to reset the recloser after the unit has automatically locked open. When the recloser is manually closed, arrangements are made to close on the second time-delay trip operation. This time-delay trip operation takes care of current inrushes and permits the recloser to trip once only after manually closing on to a fault. If no fault exists, the mechanism automatically returns to its initial position, and the recloser is ready to carry out a complete sequence of operations.

### (3.2) Reclosers of the Hold-closed Type

The operating cycle of a hold-closed recloser consists of two high-speed trip operations, followed by the recloser closing and remaining closed; transient faults are thus cleared in the same manner as with a lock-open type of recloser. If, however, a fault is persistent after the second reclosing, the recloser holds closed until the fault is cleared by some other means. After the fault current has disappeared, the recloser automatically resets and is ready for further operations. The basic time/travel curve is as shown in Fig. 2B.

In order to utilize reclosers of the hold-closed type, it is necessary to install additional fuses on the supply side of the recloser so as to protect the feeder between the recloser and the first fuse on the subsidiary circuits. The hold-closed recloser must co-ordinate with fuses on the subsidiary circuits, as for the lock-open type, and its high-speed trip operations must therefore be faster than the subsidiary-circuit fuses and, in addition, the back-up fuses on the supply side of the recloser. It is, however, no longer necessary to arrange for the recloser to co-ordinate with fuses in the event of a persistent fault, as the recloser will hold closed and co-ordination has merely to be arranged between fuses on the subsidiary circuits and the back-up fuses on the

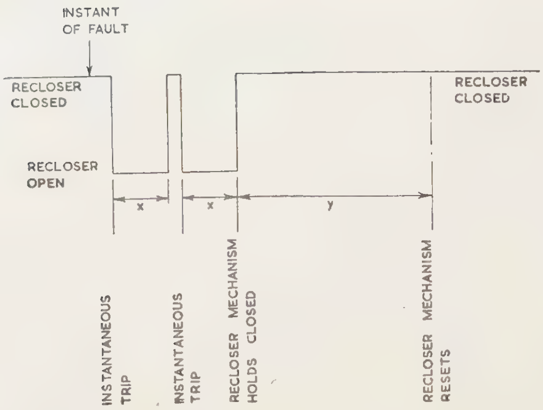



Fig. 2B.—Operating cycle of hold-closed recloser.

Open-circuit time $x$ can be selected between the limits 0·25 and 1·0 sec.
Time interval $y$ is the duration of fault current until cleared by operation of associated fuses.

main circuit. Therefore, co-ordination of hold-closed reclosers and fuses is very simple, as co-ordination is required only at the higher currents on transient faults, and the co-ordination for persistent faults is between fuses only. When selecting a recloser for fitting to lines normally protected by fuses, it is essential to match the recloser rating to the associated protecting fuse. This will ensure that the maximum protection is given to the recloser during persistent faults of low-current value when the blowing time of the fuse is relatively long.

## (4) CO-ORDINATION OF PROTECTIVE EQUIPMENT

Reclosers, when installed on an h.v. system, must have characteristics which discriminate with both the back-up and individual circuit protection utilized on the network concerned. It will be seen that the operating characteristics of the recloser vary with the fault current available on the system to be protected, and that the value of fault current may vary over a considerable range, dependent upon the position and character of the fault concerned.

When applying a recloser to any system, the following points have to receive consideration to provide adequate co-ordination:

(*a*) The normal current rating of the recloser should provide for existing load conditions and possible growth in the near future.

(*b*) The point of application of the recloser must be such that the maximum short-circuit duty does not exceed the breaking capacity of the recloser.

(*c*) Discrimination must be obtained between the recloser and the protection fitted to the substation circuit-breaker providing supply to the lines concerned.

(*d*) Where more than one recloser is installed in series, their positions and operational requirements must be such as to provide satisfactory co-ordination.

(*e*) Co-ordination should be obtained with all fuses used on the section of the system concerned over the range of fault currents to be encountered.

Fig. 3 shows typical maximum and minimum fault conditions under which co-ordination is obtained.

### (4.1) Standard Ratings

To some extent the selection of standard ratings is controlled by the MVA breaking capacity required on the system concerned. Table 3 sets out a suitable series of ratings of operating current and indicates the breaking capacity applicable.

All the ratings of reclosers would employ the same mechanism, the only difference being in the series-operating solenoid. The solenoid coils are arranged to give the same number of ampere-turns at the normal current rating of each unit. The reduction

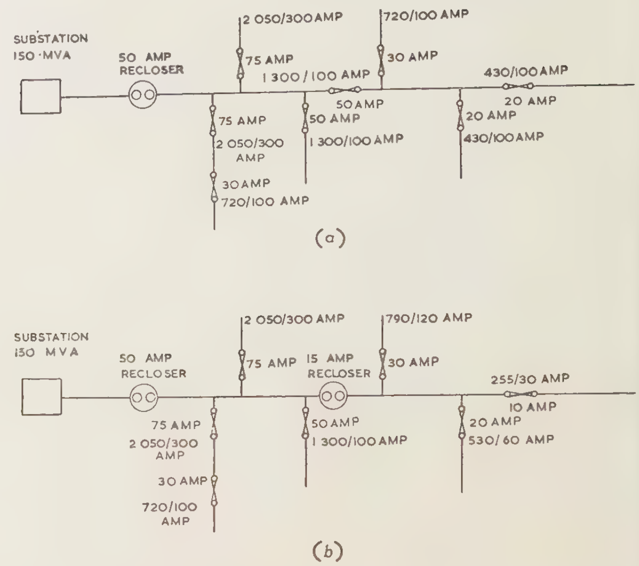



Fig. 3.—Co-ordination of protective equipment, maximum and minimum fault conditions.

(*a*) Typical layout where minimum fault current is not less than 100 amp.
(*b*) Typical layout where minimum fault current is less than 100 amp.

Table 3

RATINGS AND BREAKING CAPACITIES OF RECLOSERS

| Normal current rating | Minimum tripping current | Maximum breaking capacity in symmetrical | Equivalent 3-phase capacity at 11 kV |
|---|---|---|---|
| amp | amp | amp (r.m.s.) | MVA |
| 5 | 10 | 265 | 5 |
| 10 | 20 | 530 | 10 |
| 15 | 30 | 790 | 15 |
| 30 | 60 | 1 580 | 30 |
| 50 | 100 | 2 620 | 50 |
| 100 | 200 | 2 620 | 50 |

in breaking capacity with decreasing normal current ratings is caused by the limiting thermal capacity of the series solenoid.

### (4.2) Co-ordination of Reclosers of the Lock-Open Type with Substation Protection

Reclosers should co-ordinate with protective equipment at the main substation supplying the network concerned, so that a complete duty cycle to lock open can be performed without tripping the substation circuit-breaker.

It is usual to provide substation circuit-breakers with inverse-time overload characteristics, either by use of relays or fuse-shunted a.c. trip circuits. Where relays are used, sufficient tolerance should be allowed in the relay time selected to allow for overrun and to provide for any inching which might occur during the successive operations of the recloser, as the open-circuit time between operations may not be sufficient to allow the relay to reset completely. If the operating time of a relay or fuse-shunted trip circuit at any current is at least equal to the cumulative tripping times of the recloser, no trouble with co-ordination between the substation protection and the recloser should be experienced.

The time/current curves for the protection of typical substation circuit-breakers is shown in Fig. 4, together with the trip characteristics of the recloser. Co-ordination of reclosers with

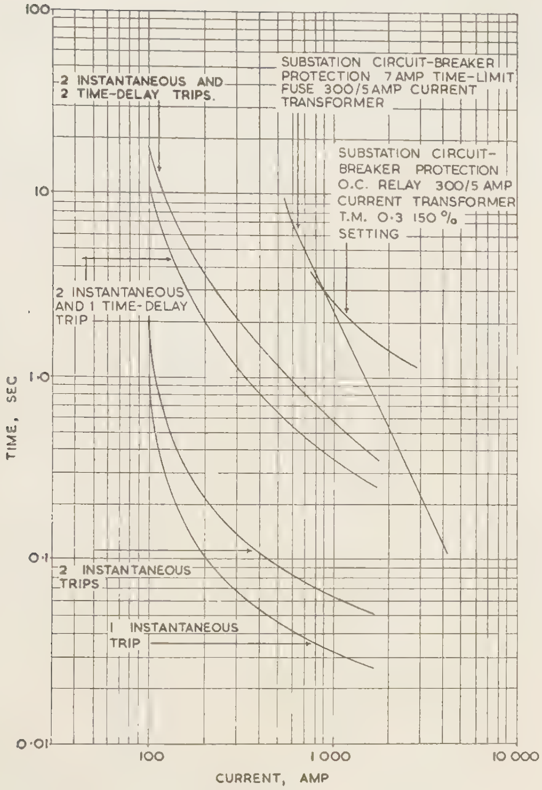



**Fig. 4.**—Co-ordination of 50-amp recloser with substation protection.

substation protection can generally be achieved, provided that the number of substation circuit-breakers in series from the actual source of supply is limited.

### (4.3) Co-ordination of Reclosers with Fuses

Reclosers of the lock-open type are required to have operating characteristics which co-ordinate with associated fuses, so that the fuses will not melt on the instantaneous trips but will melt and clear on the first or second time-delay trips.

Reclosers of the hold-closed type are required to have operating characteristics which co-ordinate with fuses only with suitable fuses to co-ordinate with these reclosers; consideration has to be given to the selection of fuses to provide discrimination over the range of fault currents to be encountered.

Up till recently British manufacturers have given much thought to obtaining fuses for use on h.v. systems which will interrupt the maximum fault energy in the minimum time. These fuses, whilst giving adequate protection, cannot be arranged to discriminate with reclosers. For use with reclosers of the type described, manufacturers have been encouraged to develop fuses specifically designed to give longer melting times without seriously impairing the interrupting capacity.

Suitable fuses of the expulsion type and of the totally-enclosed liquid-filled type are now available. The current ratings and interrupting capacities of these fuses are shown in Table 4, together with details of the high-speed type for comparison purposes.

For each rating of recloser there is a definite range of current within which it will co-ordinate correctly with any given fuse, and this range has a minimum as well as a maximum value. The maximum value is determined by the ability of a fuse to carry without detriment the through fault current during two high-speed trip operations of the recloser; allowance should therefore be made for the heating of the fuse element during the two instantaneous operations. The cooling effect during the open-circuit time is very small and can be neglected, as this tends to increase the factor of safety for discrimination purposes. The minimum value is determined by the ability of the fuse to clear fault currents of low magnitude before the recloser locks open after the final time-delay trip.

In calculating the fault current which a fuse can pass without detriment the total heating obtained must not exceed 75% of the heat needed to melt the fuse element at normal temperature. This factor allows for operating variables such as ambient temperature, degree of pre-loading and progressive deterioration due to carrying successive transient fault currents.

Fig. 5 shows the time/current curves for reclosers and slow-melting fuses.

### (4.4) Reclosers of the Lock-Open Type in Series

In applying reclosers to a widespread 11-kV network, it is desirable to install a recloser in the position where it will deal with transient faults on the maximum possible length of overhead circuit. The value of the fault current will vary considerably with the position of the fault on the network, and a recloser which is suitable for dealing with faults in its vicinity may not operate positively on faults which occur at the extreme ends of the h.v. network. Fig. 6 indicates the values of fault current at various points on an h.v. line. In order to meet cases where the minimum fault current is less than the minimum trip current of the recloser, a further recloser of smaller current rating should be installed in series. The location of the second

Table 4

RATINGS AND INTERRUPTING CAPACITIES OF TYPICAL H.V. FUSES

| Speed of melting | Type of fuse | Approximate interrupting capacities at 11 kV | Ratings available MCR | Approximate time of operation | | |
|---|---|---|---|---|---|---|
| | | | | 4 × MCR | 10 × MCR | 20 × MCR |
| | | MVA | amp | sec | sec | sec |
| Fast | Liquid | 100 | Up to 50 | 0·15 | 0·023 | 0·0056 |
| Fast | Expulsion | 50 | Up to 50 | | | |
| Slow | Liquid | 60 | Up to 50 | 3·0 | 0·47 | 0·12 |
| Slow | Expulsion | 50 | Up to 75 | | | |

under instantaneous trip operations, and an adequate range of fuses must be available to provide discrimination between fuses on subsidiary circuits and back-up fuses on the main supply system.

Where reclosers are required on lines carrying relatively small loads but with higher fault current, it will be essential to apply reclosers with a higher normal current rating than the circuit load in order to obtain the required breaking capacity, together

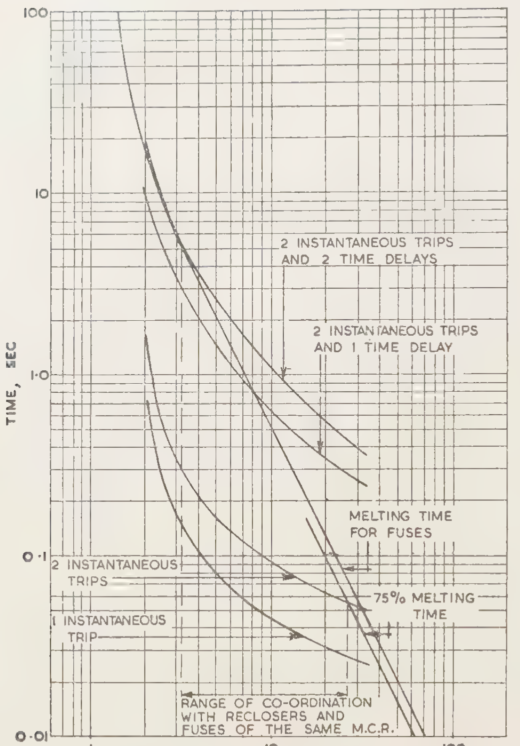



**Fig. 5.**—Current/time curves for typical reclosers and slow-blowing fuses.

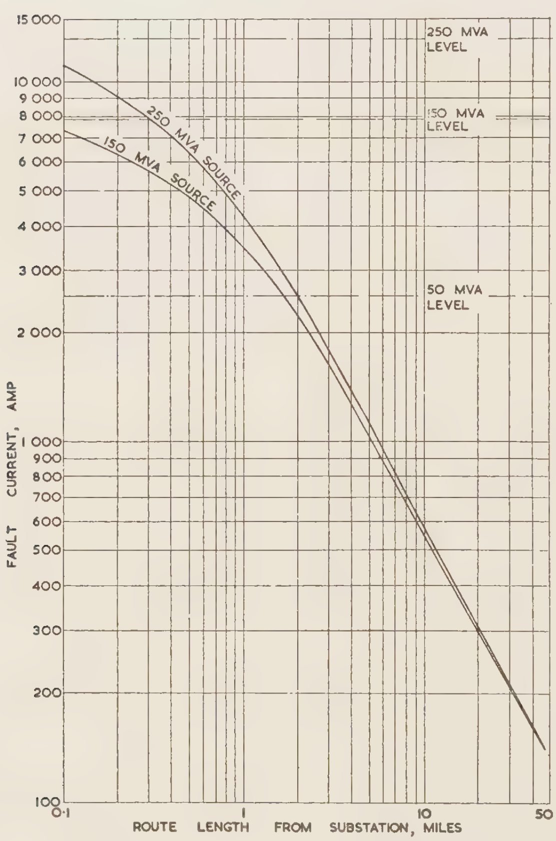



**Fig. 6.**—Variation in current for 3-phase symmetrical faults along 0·05 in$^2$ rural type h.v. lines.

recloser should be such that some overlapping of protection is provided by the first recloser, as shown in Fig. 3. By this method it is possible to improve the discrimination with fuses and in addition provide improved sectionalization in dealing with permanent faults on the main lines protected by the reclosers themselves. With reclosers in series, the recloser with the lower current rating locks out before the higher-current-rated recloser, since for a given current the time delay for a lower-current recloser is shorter.

## (5) SECTIONALIZERS

The satisfactory operation of a recloser in association with a fuse depends upon satisfactory co-ordination being obtained, and if some thought is given to the selection of suitable ratings it will be found that the majority of requirements will be met by this combination. For use where adequate co-ordination cannot be provided, however, an alternative method of sectionalization has been proposed whereby fuses can be eliminated, and a completely mechanical system comprising reclosers and sectionalizers can be adopted.

Sectionalizers are not designed to interrupt fault currents but can be set to disconnect a circuit after the second or third operation of the protecting recloser during the time when the recloser is open. This enables the recloser to restore supply to the healthy lines after the faulty section has been automatically disconnected by the sectionalizer.

A sectionalizer is a normally-closed oil switch and generally has the following features:

(*a*) It is held in the closed position by means of a prop or latch against the action of the springs tending to open it.
(*b*) It can open automatically only when no fault current is flowing.
(*c*) When a fault occurs, the current is passed through a series coil which actuates the mechanism and counts the impulses of the fault current during the operation of the protecting recloser. When a predetermined number of current impulses has been received, the sectionalizer automatically opens during the next open-circuit period of the recloser.
(*d*) Where a fault is cleared prior to the predetermined number of current impulses, the sectionalizer returns to its initial position.
(*e*) After opening, a sectionalizer must be reset manually.

As a sectionalizer has no time-sensitivity, no special co-ordination is required, and it is usual to install sectionalizers having the same normal current rating as the protecting recloser.

## (6) RECLOSERS OF AMERICAN MANUFACTURE

When the productivity team representing the electricity supply industry visited the United States in 1949, considerable interest was shown by the members in the application of reclosers of American manufacture on rural h.v. systems.

Soon after their return, arrangements were made for a number of reclosers to be purchased from America so that the operating features could be assessed when used on typical h.v. networks in this country.

Towards the end of 1951, delivery of a number of the reclosers was made, and certain of these units are now installed at suitable points on the 11-kV network of the Midlands Electricity Board, the remaining units being allocated to a special h.v. test circuit established at one of the main substations on the h.v. system.

Table 5 indicates the number and type of reclosers purchased. The general design of the reclosers is given in the next Section.

### (6.1) Dead-Tank Units

These reclosers are supplied in single-phase units and can be made suitable for 3-phase operation by mechanically interconnecting three single-phase units to provide 3-phase lock-out

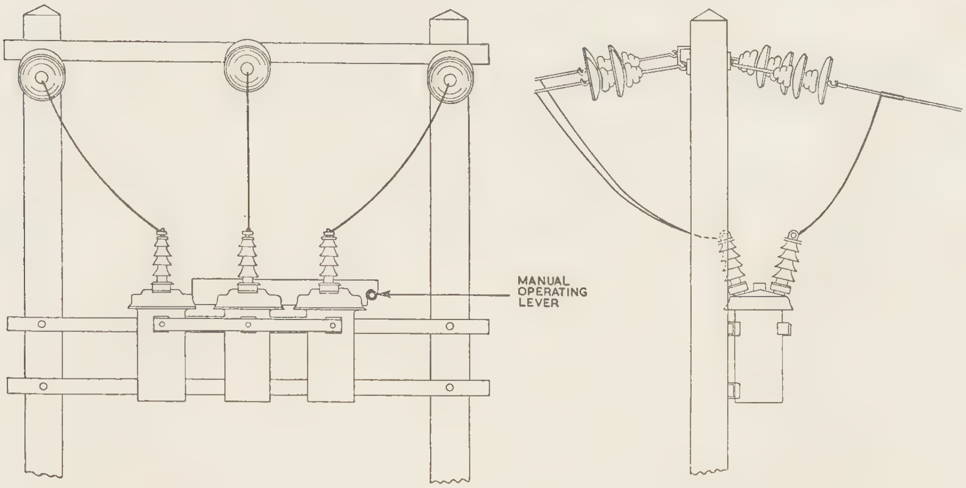



Fig. 7.—Typical method of mounting a 3-phase group of American dead-tank-type reclosers.

Table 5

TYPES OF RECLOSER IMPORTED BY MIDLANDS ELECTRICITY BOARD

| Type | Number imported | | |
|---|---|---|---|
| | For service installation | For experimental installation | Total |
| Dead tank | | | |
| (*a*) 50-amp 3-phase units .. | 3 | 1 | 4 |
| (*b*) 50-amp single-phase units | 9 | 1 | 10 |
| (*c*) 25-amp single-phase units | 6 | 4 | 10 |
| Porcelain tank | | | |
| (*a*) 100-amp single-phase units | 3 | 2 | 5 |
| (*b*) 60-amp single-phase units | 3 | 2 | 5 |
| Totals .. .. | 24 | 10 | 34 |

and manual operation. The method of installation is shown in Fig. 7.

A simple solenoid relay is incorporated in the mechanism, the armature of which is connected to a mechanical timing device. The latter offers no hindrance to the operation of the relay on the high-speed trip operations, but causes the armature to drive against the restraint of an escapement on the time-delay trip operations. The main solenoid recloser-operating coil is brought into circuit by the opening of the relay contacts. To obtain 3-phase operation, three single-phase units are provided with an interphase mechanical coupling connected to the manual operating mechanism in such a manner as to permit tripping and reclosing on the faulty phase only; but, if lock-open of the faulty phase results, all three phases are tripped and locked open. The recloser mechanism is shown in Fig. 8.

### (6.2) Porcelain Tank Units with Live Mechanism Housing

The recloser consists of a mechanism housing which is normally alive and forms one terminal of the recloser. A porcelain container is cemented on to the mechanism housing to contain the oil around the main interrupting contacts, the fixed main contact being attached to the base of the porcelain container to form the other terminal of the recloser. The main contacts are of the probe-and-socket type with Elkonite tips and are arranged to provide a single-break inside a conventional arc-control pot. The moving contact incorporates a horn-fibre extension piece to maintain alignment of the contacts when in the open position.

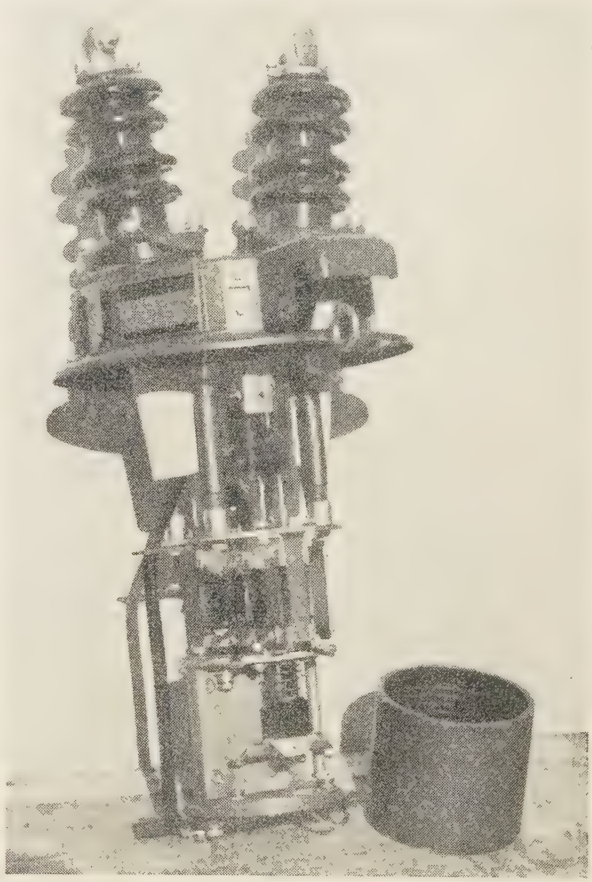


Fig. 8.—American dead-tank-type recloser with tank and arc shield removed.

A solenoid-operated relay is incorporated which, under time-delay operation, drives against the restraint of an escapement mechanism. The open-circuit time interval can be reduced by the removal of an oil dashpot, thus giving an ultra-rapid reclosing feature. No interphase mechanical coupling is possible, and the reclosers are therefore restricted to single-phase operation.

Table 6

APPLICATION OF AMERICAN TYPE RECLOSERS TO BRITISH SYSTEMS

| | Location | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Leek | Stone | Wellington | Severn Vale | Cannock | Evesham | Worcester | Bromsgrove |
| Type of recloser | Dead-tank 3–25 amp 3–50 amp single-phase in series | Dead-tank 3–50 amp single-phase | Dead-tank 1–50 amp 3-phase unit | Dead-tank 3–50 amp single-phase | Dead-tank 1–50 amp 3-phase unit | Porcelain tank 3–60 amp 3–100 amp single-phase in series | Dead-tank 3–50 amp single-phase | Dead-tank 1–50 amp 3-phase unit |
| Type of fuse | Liquid | Liquid | Liquid | Expulsion | Expulsion | Liquid | Liquid | |
| Route length of line protected | 27·7 miles | 8·3 miles | 12·0 miles | 17·4 miles | 9·1 miles | 37·4 miles | 12·6 miles | |
| Number of fused spurs | 6 | 7 | 4 | 13 | 6 | 25 | 13 | |
| Number of substations | 42 | 15 | 17 | 37 | 21 | 61 | 35 | |
| Date recloser installed | 12.12.51 | 28.1.53 | 12.4.52 | 31.5.52 | 25.9.52 | 11.6.52 | 6.11.52 | |
| Total number of operations to 1.4.54 | | | | | | | | |
| (*a*) Reclosure | 375 | 20 | 45 | 25 | 20 | 19 | 13 | |
| (*b*) Lock open | 1 | Nil | Nil | Nil | 1 | Nil | Nil | |
| Probable number of interruptions if recloser had not been self-resetting | 14 | 1 | 1 | 2 | 1 | Nil | 1 | |
| Remarks | | One unit failed in service 18.12.53. Operations are to that date | | | | | | Not yet installed |

### (6.3) Application of American-Type Reclosers to British Systems

Table 6 gives details of the reclosers of American manufacture which are installed on the h.v. systems in the Midlands Electricity Board's area.

As described previously, fuses have had to be obtained which have characteristics suitable for co-ordination with the characteristics of the recloser. Fig. 9 gives the time/current characteristics of the fuses, reclosers and back-up substation protection, from which it will be seen that satisfactory discrimination can be obtained within certain limits of fault current.

The fixed ratio of normally rated current to breaking capacity on these reclosers provides certain limitations to their use, and when selecting suitable network positions, it is necessary to take into account these limitations and to determine whether adequate co-ordination can be obtained between reclosers, and between reclosers and fuses, throughout the range of fault currents available. It is felt that this limitation must be accepted if the capital cost of reclosers is to be kept at an economical value.

Where reclosers of American type are installed on the h.v. systems in the Midlands, transient faults have no longer caused interruption of supplies. Details of the number of operations are given in Table 6.

### (6.4) Type Tests on American Reclosers

In order to confirm the operating characteristics of the reclosers obtained from America and to provide sufficient information for British fuse manufacturers to prepare designs of slow-melting fuses, a special 11-kV test circuit was erected in 1951, designed to simulate conditions normally encountered on rural-type h.v. distribution networks. The test circuit is shown diagrammatically in Fig. 10, from which it will be noted that the circuit consists mainly of 3-phase overhead lines providing supply through a number of section points and series reactors to a fault-throwing compound. Within this compound,

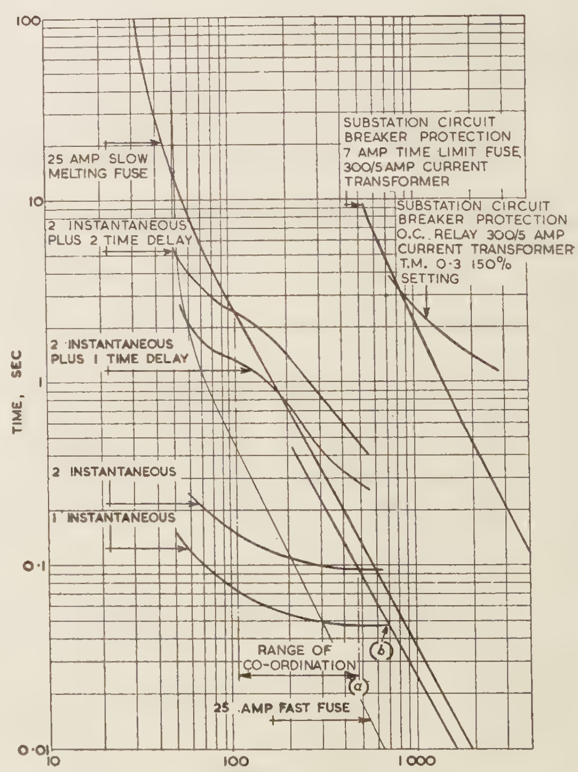



Fig. 9.—Time/current characteristics indicating co-ordination of protective equipment.

25-amp liquid fuse and 25-amp American dead-tank recloser.

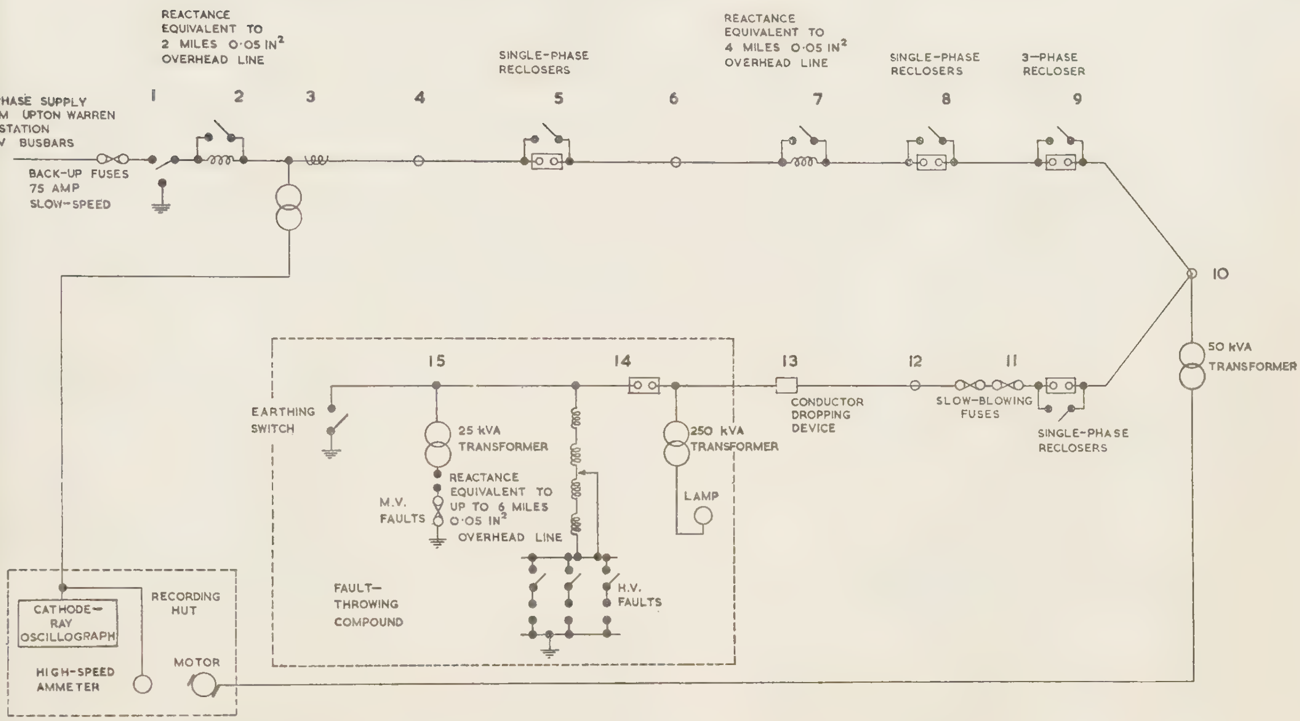



**Fig. 10.**—Single-line diagram of 3-phase 11-kV test circuit. Upton Warren substation.

aults of various types and values can be applied by the use of eries reactors connected to the main 11-kV circuit or to the ow-voltage side of a small distribution transformer. The ecessary voltage and current transformers are provided for perating cathode-ray oscillographs for recording purposes.

Under test conditions a number of reclosers of various makes nd characteristics can be installed at the pole positions on the test circuit, together with the associated h.v. network fuses, the reclosers being switched in or out of the circuit by the operation of the pole-top isolators. By this method a complete series of tests can be undertaken in the minimum amount of time.

A selection of tests undertaken on the test circuit is given in Table 7, and these show the effect of variations in the recloser and fuse combinations and the limitations of the range of co-

**Table 7**

TYPICAL TESTS ON AMERICAN RECLOSERS

| Test to show | Fault current | Recloser(s), size and type | Fuse | Recloser tripping times | | | | Recloser O.C. intervals | | | Recloser trip operations | Fuse operating time | Observations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1st fast | 2nd fast | 1st slow | 2nd slow | 1st | 2nd | 3rd | | | |
| | amp | | | sec | sec | sec | sec | sec | sec | sec | | sec | |
| Use of fast fuse .. | 318 | 50-amp Dead-tank | 25-amp Liquid | 0·05 | — | — | — | — | — | — | 1 | 0·05 | Fault cleared by fuse Simultaneous operation of recloser |
| Use of slow fuse .. | 350 | 50-amp Dead-tank | 25-amp Liquid slow | 0·045 | 0·047 | — | — | 0·802 | 0·740 | — | 2 | 0·41 | Fault cleared by fuse |
| Current below lower co-ordination limit | 120 | 25-amp Dead-tank | 25-amp Expulsion slow | 0·05 | 0·06 | 1·155 | 1·150 | 0·81 | 0·885 | 0·99 | 4 | — | Recloser locked open |
| Current above upper co-ordination limit | 705 | 50-amp Dead-tank | 15-amp Expulsion slow | 0·03 | — | — | — | — | — | — | 1 | 0·031 | Fault cleared by fuse Simultaneous operation of recloser |
| Reclosers in series | 147 | 25-amp and 50-amp Dead-tank in series | 50-amp Liquid slow | 0·049<br>0·060 | 0·045<br>0·066 | 1·132 | 1·156 | 0·835<br>0·903 | 0·920<br>0·869 | 0·996 | 4<br>2 | — | 25-amp recloser locked open. Fuse intact |
| Ultra high-speed re-closing | 307 | 60-amp Porcelain-tank | 25-amp Expulsion slow | 0·047 | Recloser arranged for one fast trip only | — | — | 0·157 | — | — | 1 | 0·583 | Fault cleared by fuse, during 1st slow trip |

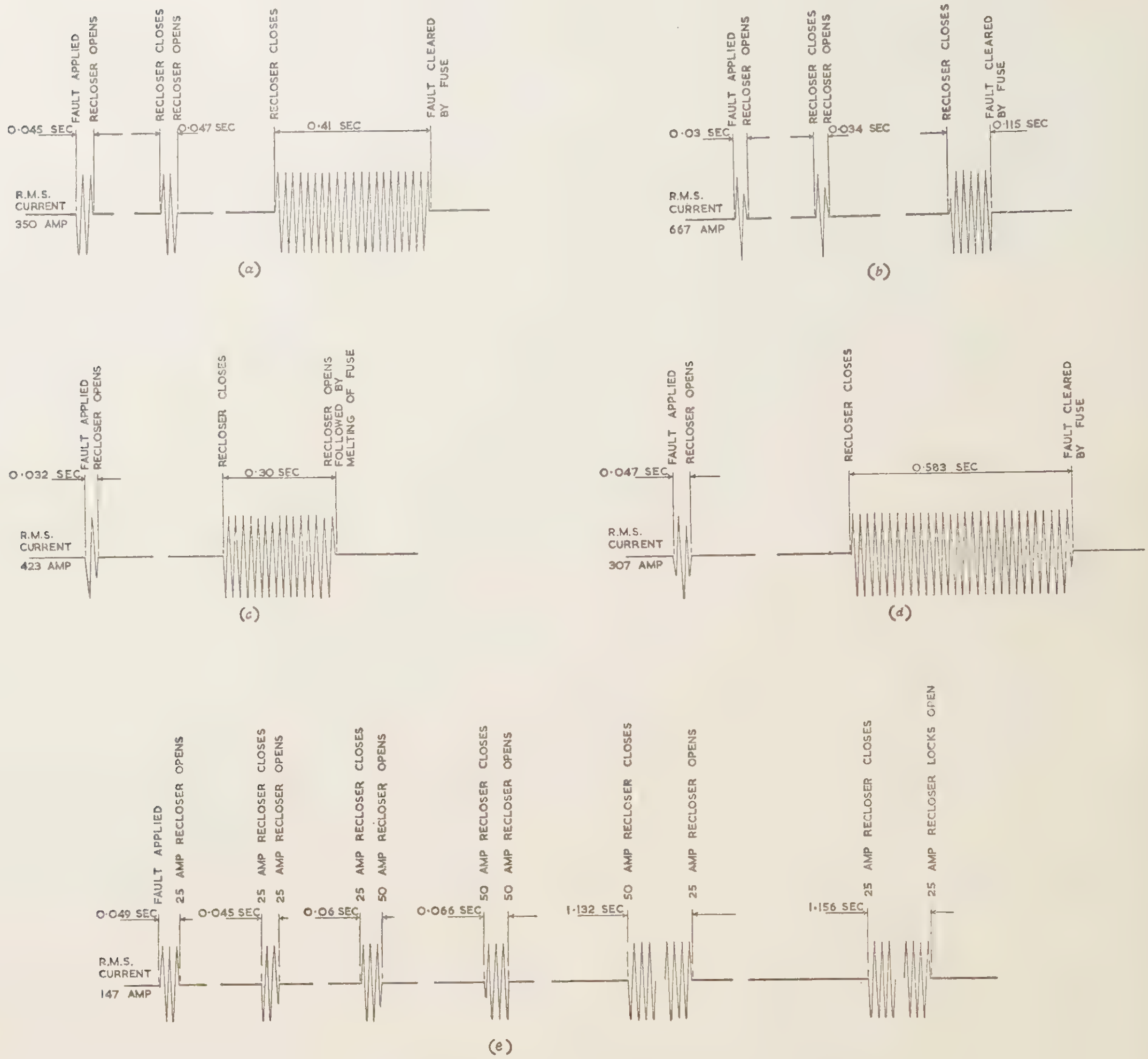



**Fig. 11.**—Typical oscillograms showing operation of American reclosers.

(*a*) and (*b*) 50-amp dead-tank recloser.
25-amp liquid-type slow fuse.
Permanent fault cleared by fuse.
(*c*) 60-amp porcelain-tank recloser.
25-amp liquid type slow fuse.
Permanent fault cleared by fuse melting during open-circuit following first slow trip.

(*d*) 60-amp porcelain-tank recloser.
25-amp liquid-type slow fuse.
Permanent fault cleared by fuse.
(*e*) 25-amp and 50-amp dead tank reclosers in series.
50-amp liquid-type slow fuse.
Permanent fault cleared by 25-amp recloser.
Fuse intact.

ordination. Oscillograph records indicating the operation on various fault currents under test conditions are shown in Fig. 11.

### (6.5) Service Experience with American-Type Reclosers

Service experience with American-type reclosers in this country is of necessity limited owing to the number of reclosers purchased and to the small number of faults on the systems protected, except in the case of abnormal system conditions which existed in the Leek District during the coastal storms of early February, 1953. In this instance, owing to heavy salt deposits on the h.v. overhead-line insulators, transient flashovers occurred over a wide area, resulting in widespread interruptions of supply. On the particular section of the h.v. network protected by two sets of reclosers in series, however, no sustained interruption occurred, although the reclosers operated 209 times in a period of 24 hours. This is an ideal example of the ability of a recloser-protected network to withstand irregular transient faults without causing inconvenience to consumers of electricity. In localitie where no reclosers were installed the heavy demands made o the operating staff by the replacement of fuses were such as t cause considerable delays in restoring supplies.

The mechanism and particularly the contact assemblies o reclosers installed have satisfactorily withstood normal operatin requirements, and it has been found that maintenance after, say 100 operations or 12 months' service, whichever is the shorte period, has been satisfactory. One electrical failure has occurre on a single-phase unit owing to the ingress of moisture throug the manual operating mechanism, causing failure of tank-line insulation followed by electrical breakdown. Mechanica failure has occurred on some 3-phase units owing to maladjust ment of the interphase coupling rods. This has not interfere with the single-phase operation of the individual reclosers, bu has prevented a satisfactory lock-out on all three phases.

In general, therefore, the limited experience obtained to dat

has indicated that reclosers of American manufacture can satisfactorily undertake the duties for which they are designed, provided the restrictions imposed by their limited co-ordination characteristics are accepted.

Experience obtained has, however, indicated the need for counters which can be easily read from ground level and for improved weatherproofing of operating mechanisms.

## (7) DEVELOPMENT OF RECLOSERS IN THIS COUNTRY

Since authority was received to obtain American-type reclosers, every effort has been made by supply engineers to persuade British manufacturers to develop reclosers suitable for use on British systems. It was necessary for the British manufacturers to give careful consideration to the production of such equipment in relation to the possible markets, both here and abroad. In addition, it was essential to prepare a design, the manufacture of which would be economical in relation to usage and operational requirements. Such a design has now been prepared and manufacture has commenced; the general characteristics of a typical British recloser are shown in Fig. 12, and its co-ordination with typical fuses is given in Table 8.

### (7.1) General Construction of a British Lock-Open-Type Recloser

The application requirements given in the Sections dealing with lock-open reclosers can be met by the automatic circuit reclosers shown in Fig. 13.

Fig. 14 is a cross-sectional view showing all the principal parts of the recloser. The top is a casting and the tank is of welded steel, which may be earthed in the usual manner.

A steel bracket is welded to the tank and provides facilities for cross-arm mounting. To prevent internal damage to the recloser against incoming voltage surges, the bushings are fitted with spark-gaps. In addition, non-linear resistors shunt the series solenoid and protect its inter-turn insulation during voltage surges. A counter and manually-operated handle are fitted under a sleet head. All the operations of the recloser are recorded by the counter, which is fitted with a reset device.

The solenoid consists of two separate windings, and by connecting these in parallel, it is possible to obtain double the normal current rating of a recloser in which the coils are connected in series.

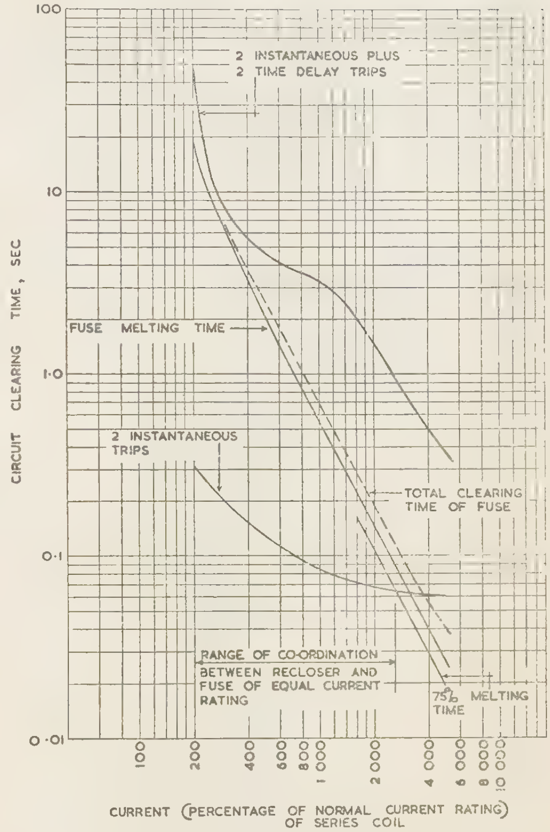



Fig. 12.—Operating characteristics of British 11-kV automatic circuit recloser.

The timing is carried out by means of a dashpot located in the switch oil, the value being determined by the orifice of an escape jet, of which a range of sizes is available to permit a corresponding variation in characteristic. Some lengthening of the time delay may be expected at very low temperatures if the recloser has not previously been warmed by the passage of load

**Table 8**

MAXIMUM AND MINIMUM VALUES OF FAULT CURRENT FOR CO-ORDINATION WITH TYPICAL SLOW-MELTING FUSES

| Recloser rating, amp | Fuse ratings, amp | Range of co-ordination, amp | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 75 |
| 5 | Min. | 10 | 45 | 50 | — | — | — | — | — | — | — |
| | Max. | 130 | 265 | 265 | — | — | — | — | — | — | — |
| 10 | Min. | 20 | 20 | 36 | 78 | 100 | 160 | — | — | — | — |
| | Max. | 115 | 270 | 300 | 530 | 530 | 530 | — | — | — | — |
| 15 | Min. | 30 | 30 | 30 | 60 | 85 | 120 | 230 | 420 | — | — |
| | Max. | 100 | 255 | 290 | 530 | 620 | 790 | 790 | 790 | — | — |
| 30 | Min. | — | 60 | 60 | 60 | 60 | 60 | 160 | 200 | 240 | 360 |
| | Max. | — | 210 | 250 | 500 | 590 | 780 | 1 100 | 1 340 | 1 580 | 1 580 |
| 50 | Min. | — | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 185 | 300 |
| | Max. | — | 140 | 175 | 430 | 530 | 720 | 1 050 | 1 300 | 1 600 | 2 050 |
| 100 | Min. | — | — | — | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| | Max. | — | — | — | 260 | 350 | 550 | 900 | 1 150 | 1 500 | 1 950 |

NOTE.—The maximum values included for all items above the thick line in the top right-hand corner are limited by the breaking capacity rating of the recloser. The minimum values included for all items below the thick line in the lower left-hand corner are limited by the minimum operating current of the recloser

Fig. 13.—British dead-tank-type recloser with tank removed.

current. The data given here are based on an oil temperature of 20° C.

The hydraulic system is sturdy and dependable and can sustain considerable shock due to heavy pulls from the solenoid magnet. A straight-line mechanism operates the contact rod, ensures minimum friction and eliminates any tendency to binding.

### (7.2) Schematics of Mechanism

To afford a simple picture of the mechanism, schematics are given in Fig. 15 at different times in the operating cycle. The oil dashpot is shown diagrammatically in Fig. 15 and indicates the exhaust valve at the base of the dashpot which is opened or closed to control the tripping times of the recloser.

The mechanism in the normally closed position is shown in Fig. 15(*a*), and indicates the fundamental principle of the recloser in the closed position. Pressure on the contacts is maintained by means of the operating spring.

During the two instantaneous operations the dashpot valve is held open to permit the dashpot plunger to travel freely in a downward direction, thus offering no hindrance to the solenoid-operating mechanism.

The passage of the predetermined current flowing through the solenoid actuates the solenoid plunger, causing it to descend as shown in Fig. 15(*b*), which indicates that the solenoid-plunger stroke is nearly completed. This movement compresses th reclosing spring and at the same time stretches the operati spring, the link mechanisms being brought to dead centre, an full pressure maintained on the main recloser contacts.

Completion of the solenoid stroke as shown in Fig. 15( causes the link mechanism to go over centre and permits th contacts to open with a snap action, irrespective of the magnitu of the current flowing in the solenoid. The combined ener stored in the accelerating spring and operating spring ensu that the correct opening speed of the contact rod is attained.

The contact rod moves freely until a sufficient gap is obtain between the fixed and moving contacts; then it is possible f the arc to be extinguished owing to the action of the arc-contr device. At this position the moving rod comes into conta with an inertia braking device which reduces its speed of trav

The reduction in the speed of the contact rod is beneficia as the time taken for the contact rod to leave the throat of th arc-control device is increased, thus enabling the arc to suppressed within the arc-control chamber during current zero

Buffering devices are provided to arrest the moving conta rod and the inertia device.

A rachet and pawl are provided as shown, the rachet bei attached to the clockwork timing-device and to the ca operating the valve at the base of the dashpot. The dashp piston is directly linked to the solenoid-operating mechanis and reclosing spring, thus controlling the times of tripping an reclosing.

On the interruption of the current, the solenoid is de-energize and the closing spring causes the linkage to reset. The spee of resetting is controlled by the upward movement of the dashp plunger, oil being dispelled through the upper jet. The tim of resetting can therefore be modified by varying the size of the je

The main recloser contacts cannot reclose until the operatin link mechanism is retracted from the upper edge of the ga latch, thus ensuring that the contacts close at the correct spee irrespective of the open-circuit time controlled by the c dashpot.

During the reclosing operation the pawl moves upwar lifting the ratchet through one step. This rotates the ca controlling the valve at the base of the dashpot and winds th time-delay device which restricts the return of the ratchet lin If an instantaneous operation of the recloser follows rapid after another, the ratchet link is moved up two steps, and th cam then releases the valve at the base of the dashpot pisto closing the exhaust port.

Should the fault current persist, the solenoid plunger ne moves against the time-delay of the oil below the dashpot pisto the time-delay operation being controlled by the release of o through the lower jet. The time of tripping under this operatio can therefore be varied by selecting suitable jets in the low position on the dashpot assembly.

During the reclosure after the first time-delay trip, the ratch link is moved up the third step, thus completing the limit of i travel.

Should the fault current still persist, the second time-dela trip follows. The movement of the ratchet link to its upp limit has resulted in a movement of the lock-out mechanism so that during the final trip operation of the recloser the upwar travel of the end of the operating lever drives the lock-ou spring mechanism upwards; thus, when the main operatin link passes over dead centre, the recloser contacts are opene and automatic reclosure is prevented by the lock-open sprin and its associated link mechanism, as shown in Fig. 15(*d*).

Where the fault does not persist during the cycle of operation the ratchet returns to its original position against the restrain of the clockwork timing device. This device provides for

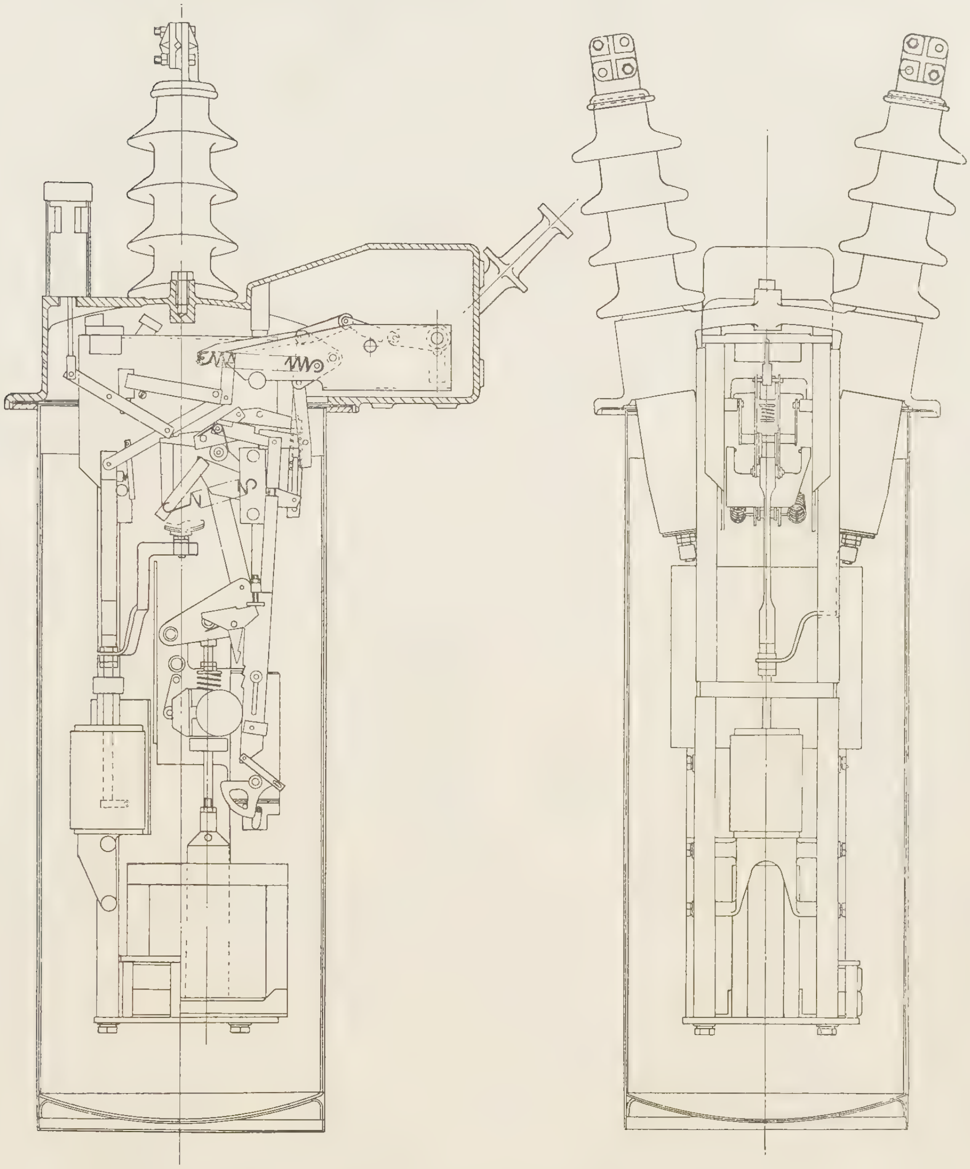


Fig. 14.—Cross-section of British lock-open-type recloser.

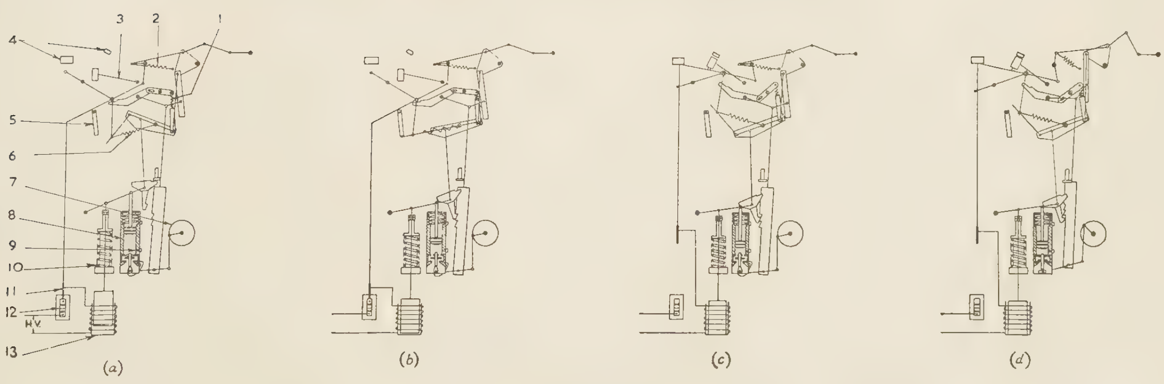



Fig. 15.—Schematics of operating mechanism of British dead-tank-type recloser.

1. Accelerating spring.
2. Lock-open spring.
3. Inertia device.
4. Buffers.
5. Gate latch.
6. Operating spring.
7. Timing device.
8. Dashpot.
9. Jet.
10. Reclosing spring.
11. Contact rod.
12. Main contacts.
13. Solenoid.

20-sec time interval for the ratchet to reset one step, thus recurring transient faults with intervals greater than 20 sec will be handled without the recloser operating under its time-delay shots.

### (8) CONSTRUCTION OF A SECTIONALIZER

Fig. 16 is a cross-sectional view of a sectionalizer suitable for application with a lock-open recloser (in this case the recloser

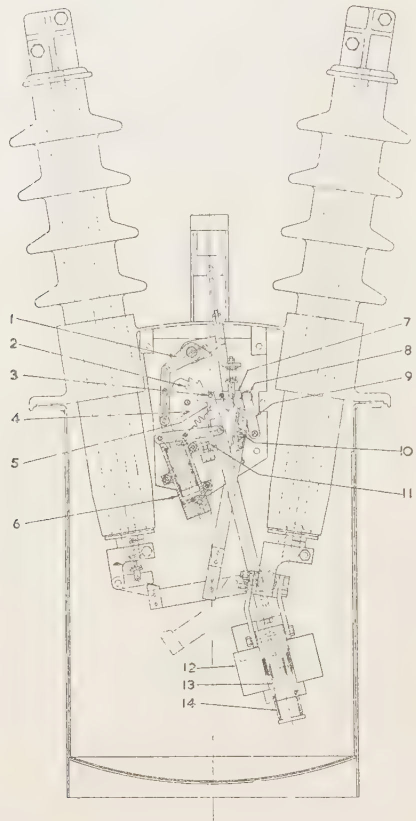



**Fig. 16.**—Cross-section of British sectionalizer.

1. Hand closing linkage.
2. Striker pin.
3. Ratchet pin.
4. Ratchet lever.
5. Pawl.
6. Dashpot.
7. Prop.
8. Prop roller.
9. Bell-crank.
10. Opening spring.
11. Adjustable stop.
12. Series operating coil.
13. Solenoid plunger.
14. Operating spring.

has four instantaneous operations) which fulfils the requirements for sectionalizers outlined in Section 5. Spark-gaps, non-linear resistors and cross-arm mounting similar to those described for the recloser are provided.

On the passage of a predetermined current through the series-operating coil, the solenoid plunger is raised and the ratchet pin on the spring-loaded pawl is lifted into engagement with the first tooth of the ratchet lever. When the recloser which co-ordinates with the sectionalizer opens and clears the fault current on the first operation, the operating spring returns the solenoid plunger to the normal position, and the ratchet pin causes the ratchet lever to rotate one tooth. When the solenoid plunger has reached the bottom of its stroke, the pawl is caused to disengage by the adjustable stop.

When the recloser remakes on a persistent fault, the sectionalizer repeats this operation but picks up on the second tooth of the ratchet lever. On the next reclosure of the recloser on to a fault, the engagement is with the third tooth.

After the third operation, when the solenoid plunger retu to its normal position, the striker pin on the ratchet lever cau the prop to rotate, releasing the prop roller and bell crank. T energy stored in the opening spring is used to open sectionalizer.

The sectionalizer must now be reclosed manually, and t is carried out by an external lever attached to the hand-closi linkage.

When two sectionalizers are used in series, the one farth from the substation is arranged to open after the second ope tion of the recloser and the sectionalizer nearest the substati after the third recloser operation.

Time-delay between operations to prevent the too rap resetting of the ratchet is provided by a dashpot.

In the case of a fault which is not persistent and is clear before the third trip of the recloser, the sectionalizer re-cyc back to normal and is ready for a further cycle of operation.

The sectionalizer is suitable for breaking twice its rated fu load current.

### (9) FUSES FOR USE WITH RECLOSERS

As mentioned previously, it is necessary to obtain h.v. fus having relatively slow-melting characteristics in order to provi satisfactory co-ordination with reclosers.

Tests were commenced in 1952 by utilizing expulsion-ty fuses equipped with elements having a slow-speed operatic Many networks throughout this country, however, are protect by liquid-filled high-rupturing-capacity rewirable fuses, and was felt that unless suitable slow-melting elements could obtained to be incorporated in the existing fuse-holders, co siderable expenditure would result in modifying fuse mountin etc.

The manufacturers of rewirable liquid fuses have therefo investigated the design and construction of slow-melting eleme for use in liquid fuses, and the cross-section of a typical eleme is shown in Fig. 17.

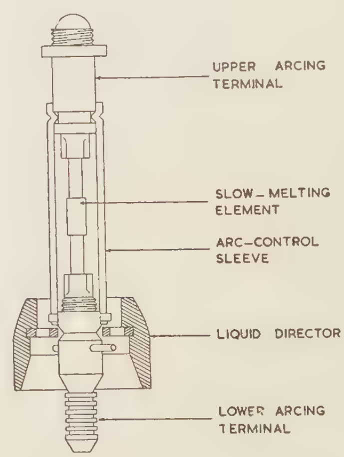



**Fig. 17.**—Cross-section of slow-melting element for liquid-type h.v. fuse.

Tests already undertaken have indicated that these eleme have suitable characteristics for use with reclosers, and t rupturing capacity of the fuse has not been seriously impaired.

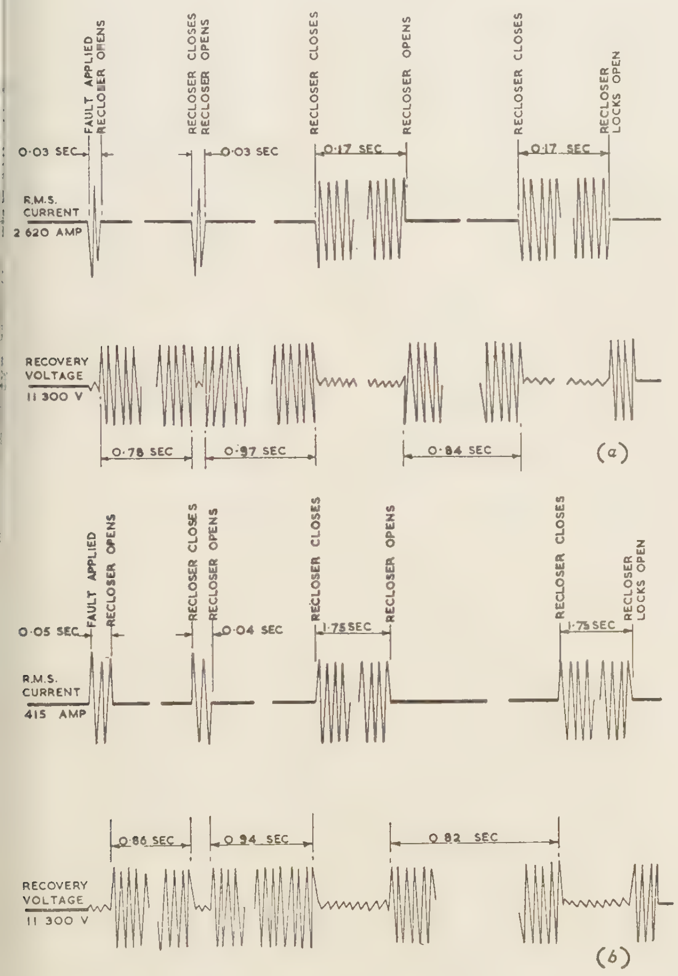
### (10) TYPE TESTS ON BRITISH RECLOSERS

The development of a recloser in this country natural involved the carrying out of a large number of tests in order prove the reliability of the design and to establish the operati characteristics and breaking capacity. As these units are a ne

evelopment, no British Standard covering their performance is et available, and no basis of testing has therefore been generally greed.

So far as breaking-capacity tests are concerned, reclosers iffer somewhat from the normal oil circuit-breaker in that the umber of operations on a particular fault may be greater.

Breaking-capacity tests to prove rating have been conducted enerally in accordance with the requirements of B.S. 116, but in lace of the 3-shot B.S. test duty, the full recloser cycle of break, nake/break, make/break, make/break has been substituted. Thus standard type-test duties comprising recloser cycles at 0, 30, 60 and 100% rated breaking capacity have been carried ut. It is recommended that the test cycle at 100% rated reaking capacity should be carried out twice, first to provide or symmetrical current on the first break of the duty cycle, and econdly to provide for the first break of the duty cycle to occur nder asymmetrical current conditions.




ig. 18.—Typical oscillograms showing 50-amp single-phase recloser operation to lock open.

The time interval between duty cycles is controlled by the hermal rating of the series opening coil and mechanical resetting ime of the recloser. In service, the majority of operations will e single instantaneous break shots with only a small proportion ecessitating make/break duty and an even less number of nstances where the full cycle of operation to lock-out is com- leted.

It has not been considered necessary to increase the thermal rating of the series-opening coil to provide a short time between full duty cycles, as it is felt that such an arrangement could not be economically justified in relation to the operating duty under service conditions. Separate tests have, however, been undertaken to establish satisfactory contact and mechanical life at varying fault currents, but for convenience these may be carried out at a reduced voltage.

It is considered that the test conditions here laid down will be considerably more onerous than those which would normally apply in service, and the life of contacts will be considerably greater than indicated in their performance on the breaking-capacity test cycles herein specified.

Fig. 18 indicates typical oscillograms for a complete recloser cycle; Fig. 18(*a*) show the operating times at the maximum breaking capacity; and Fig. 18(*b*) shows the operating times at approximately eight times the maximum continuous rating of the recloser.

As reclosers are designed for manual closing on to a fault, making-and-breaking-capacity tests have also been included to cover these operating conditions.

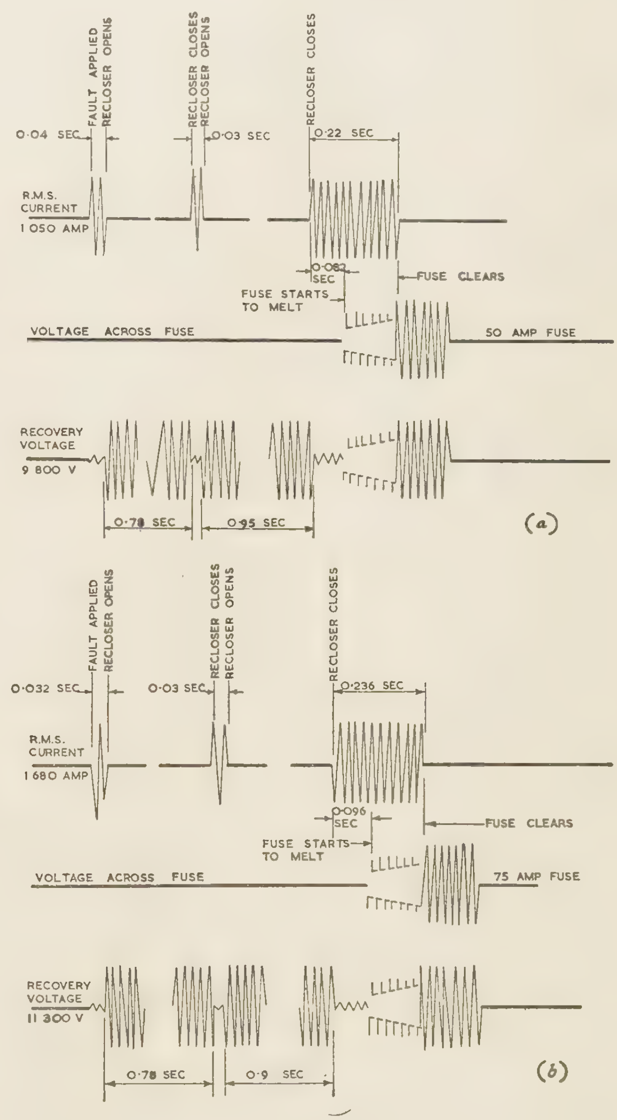



Fig. 19.—Typical oscillograms of 50-amp single-phase recloser operating in conjunction with expulsion fuses.

In order to prove the ability of the recloser to co-ordinate with fuses, a series of tests has been instituted, and typical oscillographs records are shown in Fig. 19, indicating the characteristics of a 50-amp recloser when operated in conjunction with (*a*) a 50-amp slow-melting fuse and (*b*) a 75-amp slow-melting fuse.

## (11) CONCLUSIONS

Although it is realized that the information obtained on the use of reclosers on British h.v. distribution systems is at present restricted, the authors have come to the conclusion that, provided recloser units and satisfactory co-ordinating fuses can be economically obtained, there is considerable scope for the further automatic sectionalization of many rural overhead h.v. networks.

If manufacturing costs are to be kept low, the construction of reclosers must be maintained as simple as possible. It will be realized that the co-ordination of fuses with reclosers is necessarily subject to operational limitations, as the wide range of fault currents possible on any section of a system affects the clearance time of the fuses to a very much greater extent than it does the operating time of the recloser; but the introduction of a recloser should enable a standard of continuity of supply not otherwise obtainable to be given by a single-circuit radial line. Where co-ordination of fuses is difficult, automatic line sectionalizers should prove a satisfactory alternative. Transient faults cause no inconvenience to users, as the supply is re-established so rapidly that only a flicker is apparent in lighti and rotating machinery should not fall out of step.

In addition to the improvement which should result so as maintenance of supply is concerned, operating costs should considerably reduced, as operation of fuse protection involv costly fuse replacement is limited to the occurrence of perman faults which form a very small proportion of the total fau which occur on h.v. systems in this country.

## (12) ACKNOWLEDGMENTS

The Midlands Electricity Board were authorized to investig the possible use of reclosers on British rural networks on beh of the British Electricity Authority and Area Boards, and authors appreciate the opportunity of disclosing the informati obtained. They would express their thanks to their colleag among the Engineering Staff of the Midlands Electricity Boa for assistance with the field experiments, and particularly Mr. R. Mallet, the Midlands Electricity Board's Representat on the 1949 Productivity Team to the U.S.A., whose repo and information concerning the American use of automa circuit reclosers influenced the Midlands Electricity Boar determination to investigate their use on Midland rural networ to the British Thomson-Houston Co., Ltd., for their co-operati in the development of a British recloser, and to Switchgear a Equipment, Ltd., and Johnson and Phillips, Ltd., for developi fuses having the desired characteristics.

## DISCUSSION BEFORE THE SUPPLY SECTION, 27TH APRIL, 1955

**Mr. C. H. Flurscheim:** The paper will be welcomed as a contribution to the improvement of continuity of supply. It points a contrast with the modern tendency to install switch-fuses and load-breaking isolators, which are cheaper than circuit-breakers and their associated protective gear, but imply deterioration in continuity of service. It is evident that the value of continuity should not be assessed solely in terms of energy lost, but also in terms of loss to the user and of the effect on public goodwill; it would be interesting to have the supply-industry economists' views on the capital investment justified to reduce shut-downs for different classes of distribution equipment, over and above the minimum expenditure essential for the bare function of providing a supply.

In England, rural circuit-breaker design has so far been confined to weight-operated 3-phase reclosers, which can give up to six reclosing operations without rewinding and can be arranged to lock out on sustained faults. Several thousands of these have been produced and have established the value of reclosing on rural lines. Although time-delayed reclosure has been specified by users in the past, reclosing times of the order of a second can be provided by removal of the time-delay escape mechanism.

One of the advantages possessed by the automatic circuit recloser is the self-rewinding feature. This can be particularly valuable if the recloser is far out on the line and the fault power small, but if the recloser is situated near a substation and is subject to a fault power of the order of 50 MVA, the number of reclosures permissible without maintenance is likely to be restricted to the same order as with a weight-operated recloser. The self-rewinding feature, however, gives no warning of the need for maintenance and may result in the circuit-breaker destroying itself. In these circumstances the weight-operated recloser is self-protecting in that rewinding is necessary and warning is given to the maintenance crews. It therefore appears that the self-rewinding recloser is especially suitable for remote installations, and the weight-reset unit, possibly with the addition of relay discrimination, for situations near substations wh faults may be large and where the circuit-breakers are mo accessible for rewinding.

A further division of application seems to be indicated by t frequency of faults to be expected, which varies widely on differe lines, as is shown in Table 6. Those lines which exhibit possibility of saving one shut-down in two years by conversi to reclosers may be border-line cases on any assessment of t value of continuity.

The British recloser described in the paper represents a st forward in design, for one of the deterrents to development this class of equipment has been the complication and cost the time-delay escapements and mechanisms required. The u of oil delay gear is a logical step towards simplification, althou the mechanism is still an intricate device.

Considering the test duties for rural circuit-breakers, I f that it is possible to prejudice the design unduly by requiring t severe circuit conditions. In practice, quite low power facto are likely to be encountered, and tests at power factors of 0·3 even higher should be representative of service conditions rural lines.

**Mr. G. O. McLean:** The authors' figure of 80% for the numb of temporary faults seems rather high; a check made for tw Sub-Areas that are truly rural (using the authors' yardstic gives 57 and 55% respectively. Details in a form similar Table 1 are given in Table A. In a paper giving the nation fault statistics for 1951–52, the figure was 69%; this may ha been near enough to the authors' 79% not to cavil at it, but t definition of transient or temporary faults is one of the autho own making, i.e. a temporary or transient fault is one that do not damage the equipment. Surely transient or temporary fau should have a time basis, and this has been ignored.

Some of the faults listed in Table 1 would make the reclos go through its complete cycle and lock open—particularly t "unknown" and the "cattle" items—for these may invol durations of minutes rather than seconds. I think some of t

Table A

| Cause | Taunton Sub-Area | | | | Cornwall Sub-Area | | | |
|---|---|---|---|---|---|---|---|---|
| | Transient | Persistent | Total | Transient/Total (%) | Transient | Persistent | Total | Transient/Total (%) |
| Lightning | 32 | 15 | 47 | 68·1 | 17 | 15 | 32 | 53·2 |
| Unknown | 30 | — | 30 | 100·0 | 24 | — | 24 | 100·0 |
| Weather | 10 | 8 | 18 | 55·7 | 32 | 9 | 41 | 78·1 |
| Animals | 2 | 1 | 3 | 66·7 | — | — | — | — |
| Birds | 18 | 1 | 19 | 95·0 | 7 | 2 | 9 | 77·8 |
| Windborne objects and trees | 9 | 5 | 14 | 64·3 | 5 | 11 | 14 | 35·7 |
| Conductors | — | 4 | 4 | — | — | 6 | 6 | — |
| Binders, clamps, joints and jumpers | — | 8 | 8 | — | — | 13 | 13 | — |
| Insulators | — | 21 | 21 | — | — | 7 | 7 | — |
| Line supports | — | 1 | 1 | — | — | 1 | 1 | — |
| Surges | — | — | — | — | — | 1 | 1 | — |
| Miscellaneous | — | 14 | 14 | — | — | 6 | 6 | — |
| TOTALS | 101 | 78 | 179 | 56·7 | 85 | 71 | 156 | 54·5 |

9% should be reduced, and the reclosers will probably help by bout 50%.

Table 1 shows lightning as being responsible for about 50% of the total faults. The authors do not refer in the paper to the mpulse withstand voltage of the circuit-breaker, which I consider mportant. I presume that it will be to the new B.S. 116 (in lraft), which is 95 kV. It is important to know the voltage, or lightning is our principal worry in rural areas; the recloser tself should be able to withstand 95 kV surges.

In Sections 3 and 4 the authors deal very fairly with the hold-losed and the lock-open reclosers. My reading of these ections leads me to favour the hold-closed type, and I am urprised to read that British manufacturers prefer the lock-open ype. The principal advantage of the hold-closed recloser is that t offers less trouble with co-ordination: it is necessary to o-ordinate only fuse against fuse, which is fairly easy, and not use against recloser. It comes as a surprise to see that the uthors sponsor the lock-open type.

The sectionalizer is a valuable piece of equipment, but the ype discussed in Section 5 has apparently not learnt to count eyond two; we want something that will count up to at least ive or six, to give more steps in the grading of protection between he main substation circuit-breaker and the final spur line.

**Mr. O. M. White:** I am particularly impressed with the nalysis of faults. The authors have covered nearly every ontingency—even the hazard mentioned by an insulator manuacturer the other day as the only one which would affect his roduct, namely disappointed hunters. I presume that the lines o which the analysis refers are those conforming with B.S. 1320, which should be less affected by lightning, earth faults and other ransients. I notice that the faults due to birds at mid-span re considerably greater than those at the insulators.

It is sometimes contended that a few pounds spent on fault revention may save a lot on cure, but complete immunity is mpossible to achieve and the authors' scheme seems very ffective for minimizing interruptions due to faults which cannot conomically be avoided.

The authors refer to attention after 100 operations, or once a ear. Is skilled maintenance required or can the ordinary perating staff deal with it?

Have the authors considered the possibility of using reclosers or the protection of series condensers? These are coming more nd more into use and protection against current surges is ssential.

**Mr. K. M. Jones:** From Table 1 it is evident that the majority of faults are transient, and it would therefore appear pertinent to consider the performance which could be obtained if arc-suppression coils had been used instead of reclosers. Unfortunately the Table does not indicate how many of the faults involved more than one phase, but with lines constructed to B.S. 1320, i.e. unearthed construction, it would be expected that the majority of faults would be inter-phase and that the scope of arc-suppression coils would thus be limited, since they can deal only with phase-to-earth faults. Will the authors comment on the probable distribution of inter-phase and phase-to-earth faults on the lines in use on their system?

However, let us assume for the moment that the majority of faults would be single line-to-earth faults and that arc-suppression coils are therefore a possibility. Does their application entail any difficulties? For the type of system being considered the answer must be a qualified affirmative. For example, spurs are used, and it is therefore possible for the capacitances to become unbalanced when a fuse blows. This results in a permanent displacement of the neutral until the balance is restored, e.g. a 5% capacitance unbalance can result in a neutral displacement of about 50%. When a section of the system is lost it is necessary to retune the coil if effective operation is to be maintained; with reclosers no action is necessary apart from fault location—which is common to both methods. With growth of the system it is essential to add other arc-suppression coils in parallel, whereas with reclosers probably in many cases only the series coil has to be replaced. With an extensive system, parallel routing with other networks is probable in this country, and the zero sequence voltage induced in the conductors of a system earthed through arc-suppression coils can result in a considerable displacement of the neutral of that system. Typically, the amplification of the induced voltage could be 30. Apart from the increase in phase-to-earth voltages on the arc-suppression-coil system, the indication would be of a fault on the system when no fault existed.

It is stated that where co-ordination cannot be obtained with fuses, reclosers can be used in conjunction with sectionalizers. In America sectionalizers have been used on a large scale and have generally been found satisfactory. However, maloperation has been known to occur as the result of a high fault impedance of rapidly varying magnitude; apparently in counting the current pulses the sectionalizer included some due to the fluctuating fault current. On this particular system operators have

been advised to expect this kind of trouble occasionally. Would the authors comment on the probable extent of the use of sectionalizers in this country?

In production testing of the British recloser a check on the timed periods of the operating cycle is required for each circuit-breaker under short-circuit conditions, so that on-the-spot adjustments may be made if necessary. The delay in processing film prohibits the use of an oscillograph, and a timer capable of simultaneous display of the five timed periods has been developed. The timer consists of five Dekatron units each capable of indicating to within 0·01 sec. A special electronic selector circuit is employed to count the number of applications and removals of short-circuit current caused by the operation of the recloser, and to energize each timing unit in turn at the correct moment and for the correct period.

**Mr. R. A. Woods:** Most distribution engineers will agree with the authors that there is a good case for more automatic reclosing on distribution networks, and the paper sets out very clearly the advantages of high-speed reclosers of either the lock-open or the hold-closed type, compared with automatic reclosing circuit-breakers of the weight-operated type.

Fig. 4 indicates the co-ordination between substation protection and the recloser, and it will be observed that the substation relay setting is extremely high, namely 450 amp, the time multiplier being 0·3. Moreover, on overhead networks it is generally desirable to have earth-fault protection, the setting of which would also have to be co-ordinated with the recloser characteristic.

The authors mention that the break-back feature of the characteristic shown in Fig. 12 was introduced to facilitate grading of the circuit protection, but I feel that grading of i.d.m.t. relays would be considerably easier if this feature were omitted. For a 50 amp recloser it is found that the first portion of the summation curve corresponds approximately to the curve of a relay set of 60 amp, the time multiplier being 1·0, using the standard relay characteristic given in Table 7 of B.S. 142. However, the second portion of the curve, for currents exceeding 1 kA, conforms closely to a relay setting of 600 amp, the time multiplier being 0·125. When grading a relay with a recloser one has therefore to adopt a compromise between these two differing characteristics. It would be very helpful if the characteristic of the delay trip could be altered to a uniform curve corresponding, for a 50 amp recloser, to an i.d.m.t. relay setting of the order of 200 amp, the time multiplier being 0·25.

The authors mention that a 1 sec interval will not allow for full resetting of the relay. This, I feel, is an understatement, since inverse time relays normally take 10 or 11 sec to reset from full setting. Overswing will also tend to prevent resetting during such a short time interval.

The use of powder-filled fuses with reclosers is not mentioned in the paper; have the authors had any experience of co-ordination with slow-acting fuses of this type?

In the British recloser the series coil is in circuit continuously, whereas I understand that in the American type it is short-circuited during normal operation. What are the losses in the series coil?

On the question of ratings, I suggest that there will not be much use for the 15 amp size in this country and that a rating of, say, 60/30 amp would probably meet the majority of our requirements.

**Mr. A. C. Gibson:** The paper refers to two types of American recloser—the porcelain-clad and the dead-tank types. The dead-tank type was adopted for the British unit because it enabled simple interconnection of phases to be obtained, so that 3-phase tripping can be accomplished. With the porcelain-clad unit, however, the mechanism head forms one of the terminals, and it would be necessary to employ insulation coupling members between each single-pole unit.

American units having the operating coils shunted by re contacts have been mentioned. This applies only to cert American styles, and units with single operating coils are used many cases. It was felt that, if two electro-mechanical functi had to operate to open the contacts, the unit could not give fastest instantaneous trip. If discrimination with fuses transient faults is to be obtained it is essential for the first t trips to be as short as possible—and that consistently. A sing coil unit was therefore adopted. When one considers difference between the 2-coil and the single-coil unit it can seen that the former is relatively lighter and permits the use an escapement form of timing mechanism coupled to the re magnet. With the single-coil unit, however, the heavy for which have to be handled when operating on full short-circ rule out a mechanical timer, and an oil dashpot is the o method which can be introduced to control the time tri Criticism has been made of the use of an oil dashpot, owing the variation of timing with temperature change that it involv but tests have shown that such variations are not likely to troublesome.

During routine tests on the production units each dashpo first checked for timing at five different pressures, to ensure t it complies with the basic characteristics before it is assemb in the recloser. After complete assembly each unit is wash by oil jets to remove any foreign particles, and after calibrat so that the unit operates at twice the rated current of the c complete operation cycles are carried out at four currents rang from 125 to 1 000% of the calibration current; the open tin and the time-delay trips are checked and recorded by means the Dekatron (described by Mr. Jones). These tests ensure t every unit is operating correctly and that it will comply with basic current/time curve within very close limits. When th electrical tests are being performed each unit is coupled w master heads to check operation for 2- or 3-pole coupling.

**Dr. R. H. Golde:** In connection with Table 1 I should like authors' definition of the term "supply interruption," particula in cases of simultaneous operation of tee-off and individ transformer fuses on spurs with several transformer installatio Again, in the first column of Table 1 the heading "cause interruption" includes not only lightning, birds, cattle, verr and so on, but also cables, insulators, switchgear and conducto How are the figures to be interpreted? For example, there 65 "permanent interruptions" due to lightning, in addition to multiplicity of interruptions listed under cables, insulators, e Are these included in the 65 "permanent interruptions" due lightning or other natural causes? If this is so, the total figu do not give a true picture. Incidentally, in view of the mislead impression it creates, I suggest replacing the term "perman interruption" by "persistent interruption."

In Fig. 3(*a*) a 30 amp fuse is indicated on one spur, and series with it is a 50 amp fuse on the main line. The 30 a fuse is liable to be subjected to a large number of fault curren particularly under lightning conditions when flashover occurs terminal transformers. This fuse may therefore be replac more frequently than the major 50 amp fuse, which will repeate carry fault currents without operating. The 50 amp fuse m thus be weakened to such an extent that discrimination betwe the 30 and 50 amp fuses could not be maintained. In Americ practice discrimination between fuses with such close ratin would not normally be expected.

In Fig. 13 arcing horns are shown across the bushings of recloser, the metal case of which is said to be earthed. T seems to present a risk of a persistent fault due to birds at recloser. Why is the normal practice of using duplex gaps followed, and is it not possible to make the top of the circu breaker of insulating material instead of metal?

The authors have presented a clear case for their contention that the number of transient supply interruptions in a system would be greatly reduced by the installation of automatic reclosers. This claim can, I think, be further strengthened. If a flashover occurs over an insulator, or over the arcing horns of an oil circuit-breaker or a transformer bushing, and if the fault current is allowed to flow for a second or more, the insulator or the bushing may be damaged by the arc and a persistent interruption may result. The same argument may even apply to transformer windings. There is strong reason to believe that a considerable number of transformer failures start as transient faults but are converted into persistent faults as the result of the duration of the fault current. I therefore believe that the introduction of the automatic recloser will cause a reduction in the number of persistent faults in addition to the large decrease in the number of transient interruptions expected by the authors.

Finally, I believe that this paper will be regarded in the future as a landmark in the maintenance of continuity of supply in British supply systems.

**Mr. E. Hywel Jones:** At a very small hydro-electric station with three sets feeding into the local Area Board system the Board have recently changed their voltage and now provide a supply with automatic reclosing. The hydro-electric sets could have their voltage and number of phases changed, but it is difficult to see how they could continue to generate in view of the adoption of this type of protection on the connected system. Is there a cheap method of retaining small stations of this type in service while using automatic reclosing? This particular case may not be important, but if wind generators are to be adopted on a large scale and applied to systems where automatic reclosing is in use, the problem may well repay attention.

**Mr. J. E. Peters:** The authors recommend maintenance after 100 operations or 12 months' service. Do they intend to carry out the work *in situ* or at a depot? In order to carry out maintenance it will be necessary either to provide a short-circuiting switch and isolators so as to disconnect the device and make it safe for work (which adds to the capital cost and makes it more difficult to justify the recloser economically) or to prearrange a shut-down. Have the authors considered isolation by means of "live line" working?

**Mr. R. Mallet:** The reclosers have a withstand voltage in excess of 95 kV, so that they would be quite suitable without surge diverters for inter-phase flashover under lightning surge conditions. If they were earthed, however, they would introduce a point of great weakness on an unearthed line.

For maintenance, it is necessary to bring the unit into a workshop, replacing it with a serviced unit. This can be done without providing a line-short-circuiting switch or interrupting the supply, by using live-line taps and a short-circuiting jumper. A special form of mounting has been designed and the procedure suggested above has been successfully tried on an unenergized line. No difficulties are anticipated in doing the same thing on an energized line, for the equipment used has already been tried out on a line working at 11 kV.

**Mr. P. E. Gaze** also contributed to the discussion at London.

[The authors' reply to the above discussion will be found on page 770.]

## NORTH-WESTERN SUPPLY GROUP, AT MANCHESTER, 11TH JANUARY, 1955

**Mr. F. Mather:** The paper is particularly appropriate at a time when great emphasis is being placed on rural electrification in Britain and supply engineers are endeavouring to achieve the correct balance between complete continuity of supply and high capital cost. However, the automatic recloser is appreciably dearer than the orthodox auto-reclosing circuit-breaker, and rough calculations indicate that the annual charges on one 3-phase set of reclosers would absorb about 0·5% of the total revenue from an average rural load of 1 MW. To what extent should we spend capital on reclosers in order to improve continuity of supply, avoid loss of revenue due to shut-downs, reduce the cost of fuse replacements and minimize the time spent by engineers in dealing with transient faults?

I understand that in the rural areas of the United States there are many primary substations of 1–5 MVA capacity, so that the fault rating on the h.v. distribution system is not high and the relatively low breaking capacity of the recloser is not a disadvantage. I gather that in such cases it is the practice to use reclosers instead of oil circuit-breakers for the control of the main outgoing feeders at the substation, and that by doing so not only are the advantages of the recloser obtained but there is also a reduction in capital cost over the more orthodox arrangement. Is this a correct impression of practice in the United States?

The absence of earth-fault protection may cause some difficulty, particularly if reclosers of the higher ratings are used in conjunction with unearthed line construction. Considerable attention will be necessary in such cases to the adequacy of earthing electrodes at pole transformers, section switches, etc. Possibly it is for this reason that some of the American companies offer reclosers with earth-fault protection.

The authors do not mention any form of lightning protection for the recloser itself, whereas in some American literature the recommendation is made that line reclosers should be protected by lightning arresters at each side, and substation reclosers by arresters on the outgoing side. Do the authors consider such precautions necessary in Britain?

**Mr. L. F. Ryland:** In 1952 I visited the experimental station referred to in the paper and it was then considered that the recloser could serve a useful purpose on many of our rural networks, a possible difficulty being the 50 MVA breaking-capacity limit of the recloser, since many of our rural networks are fed from substations containing 150 or 250 MVA switchgear. Fig. 6 indicates that with a $0 \cdot 05\,in^2$ line the fault level diminishes so rapidly that beyond a radius of about $1\frac{1}{2}$ miles an automatic recloser could be safely used. What percentage of our total rural network lies beyond a $1\frac{1}{2}$-mile radius of the feeder substations?

It seems that one high-speed and one time-delay trip operation would cater for most requirements. Would this appreciably cheapen the automatic recloser?

Is an open recloser considered sufficiently safe for men to work on an overhead line, or would back-up isolating switches have to be fitted?

In Fig. 3(*a*) a 50 amp recloser is shown feeding fuse circuits aggregating 250 amp. Even allowing for diversity of load, it would appear that the recloser will be overloaded at peak periods. Moreover, the 50 amp rating limits the usefulness of the line which could otherwise carry much more than this.

Widespread use of the reclosers in this country will depend on whether the manufacturers can supply reclosers at an economic price, bearing in mind the rather limited numbers likely to be required.

**Mr. W. Larkum:** I have been interested in automatic-reclose switches for a considerable number of years, and in 1940 installed several of the weight-operated type. Except for a few troubles in the first week or so, these switches have given excellent service over the past 15 years.

The Sub-Area in which I am employed suffered severe damage

during the period when the reclosers on the Leek section of the Midlands Electricity Board operated 209 times in 24 hours. In the course of a few days one hundred and thirty 11 kV insulators failed, while numerous lines burned through and fell to the ground. If these circuits had been protected by the type of recloser described many outages might have been avoided, with a reduction of damage to the circuits.

I should like the authors' views on the use of this type of switch on ring mains. With the dropping-weight switch the current-coil values do not give any discrimination, and my experience was such that, by setting the spur feeders with two reclosures and the main-line switches with three, a fault occurring on the spur line would trip all switches but would finally leave the main line energized by means of the additional reclosure. Would it be possible to install switches having two slow-tripping times at each end of the line and one with only one slow trip in the middle of the circuit, so that with a persistent fault on one side of the line this section would be isolated while the other section would still carry a supply?

It would seem that surges can be cleared quickly on lines conforming with B.S. 1320. Would it be an advantage to have selected points along such lines where the impulse levels are reduced, so that surges could be removed from the line more easily and thus other equipment would be less prone to damage by them?

**Mr. W. A. McNeill:** Any method of reducing the cost of distributing electrical energy in rural areas must deserve serious consideration, and provided that the system is designed to suit the automatic recloser, this form of control can give excellent results.

The success or failure of the recloser will depend on the economic advantages achieved, and I regret that the authors have not enlarged on this aspect. In particular, the equipment will have to be manufactured in large quantities to compete with the low costs that have been achieved in America. In this respect, the authors state that every effort has been made to persuade British manufacturers to undertake developments, and while it is true that interest in the project has been evinced, very few supply engineers in this country have been prepared to hazard even a guess at the likely demand. The most successful American manufacturer of reclosers was manufacturing upwards of 20 000 units a year in 1950. The selling price for the British article would have to be competitive, not only at home, but also in oversea markets.

Has full consideration been given to all the available American types of recloser, and to the extensive literature which has been published in the United States? The impression is gained that the authors' experience has been limited to two types only, no mention being made of the very successful recloser which relies entirely on a hydraulic mechanism for the sequence control. It is claimed that this mechanism is less prone to maloperation by shock than is the type incorporating a clockwork mechanis[m] and that changes in temperature have had a negligible effect [on] its operation.

When this project was first discussed with British engineers [the] objection was the method of installation without isolators. [It] was thought that the requirements of the Factories Act would [be] infringed and that the American practice of live-line maintena[nce] would not be tolerated here. I should like the authors' views [on] this point.

Short-circuit tests have been carried out to B.S. 116, but th[e] test series appears to be inadequate for a device whose duties a[re] very different from those of a standard oil circuit-breaker. N[o] reference is made to the American Test Code in A.I.E.E. 50: 19[..] or to later revisions. This specification called for 100 unit ope[ra]tions at fault currents ranging from 10 to 100% of the reclo[ser] rating and at specified power factors. Unless a representat[ive] number of tests is carried out it is difficult to assess the co[n]sistency of the device for the co-ordinating duty required. T[he] authors give only typical test data on the British recloser [in] Section 10, and do not reveal arcing times below 16% of [the] rating. Co-ordination, however, is claimed down to 200% [of] normal current, or to 3·8% of the short-circuit rating. It wou[ld] add to the value of the paper if the performance data we[re] amplified.

It would also be of interest to know to what extent the sho[rt]-circuit performances of the fuses, referred to in Section 9, ha[ve] been impaired in order to obtain the slow-melting characteristi[c].

**Mr. H. Shackleton:** The years 1953 and 1954 should not [be] taken as being typical of our English weather, although t[he] statistics for 1953 quoted in the paper give a good indication [of] the possibilities of automatic circuit reclosers. On the No[rth]-Western Board's 11 and 6·6 kV overhead systems 80% of t[he] 1 000 outages due to lightning over a period of two years, and 50[%] of 2 000 outages due to causes other than lightning over a peri[od] of three years, did not involve any permanent damage. It wou[ld] therefore seem that the proportion of interruptions involving [a] permanent damage is rather higher in the midlands than in t[he] north-west. This may be due partly to the method of collection [of] statistics, since in the Midlands Area counters were used o[n a] number of circuits so that each transient interruption would [be] recorded, whereas in the north-west very few counters are e[m]ployed and a circuit which was reclosed two or three times co[n]secutively would record only one interruption.

Since the normal current rating of a recloser seems to [be] determined largely by the associated solenoid, the British ty[pe] described in Section 7.1 would appear to have some advantag[e].

I suggest that the footnotes to Table 8 might be clarified w[ith] advantage.

[The authors' reply to the above discussion will be found [on] page 770.]

## NORTH-EASTERN CENTRE AT NEWCASTLE UPON TYNE, 14TH MARCH, 1955

**Mr. C. G. Whibley:** The original American recloser was developed for long and relatively inaccessible lightly-loaded phase-neutral lines. The original simple plain-break low-fault-rating single-phase unit has developed until it is now being produced in various forms, including 3-phase construction with common operating mechanism.

Rural distribution in this country is being based mainly upon the unearthed 3-phase construction to B.S. 1320, using phase-phase spurs. To clear permanent faults and to prevent any inadvertent cross-country earth currents from the faulted phase it will be necessary to equip each conductor of the 3-phase or phase-phase line with a recloser contact and lock-out.

The authors' design retains single-phase construction. What are the practical and economic aspects of coupled single-pha[se] units compared with designs specifically setting out to cater f[or] 3-phase and phase-phase working?

One of the main uses of sectionalizers is to provide a means [of] isolating a section of line when it is not possible to obta[in] adequate discrimination by using fuses. In reviewing the possib[le] service conditions in this country, have the authors formed a[n] opinion on the extent to which sectionalizers will be required?

**Mr. P. E. Gaze:** For these devices a large number of operatio[ns] can be expected, and maintenance requirements must be a mi[ni]mum; maximum mechanical reliability is therefore essential. [A] 10 000-operation life test is accordingly being carried out, a[nd] since this must necessarily involve the breaking of current, it w[...]

give a good reproduction of service conditions. It will be seen from the paper that the great majority of faults experienced in service are likely to be transient faults cleared at the first instantaneous trips, and the majority of shots in the life test will thus be on a break-make-break cycle; but a proportion will include the full duty cycle of four interruptions followed by lock-out.

Owing to the very rapid reduction in fault level with distance from the energy source, a very high proportion of the faults experienced in service by reclosers will be below the maximum fault level. In the life test, therefore, a high proportion of shots will be taken on operating currents representing the lower fault levels.

In the method of testing employed the recloser is connected in the high-voltage circuit of a transformer and faults are applied by short-circuiting the low-voltage winding. This permits full voltage to be retained on the recloser after the fault has been removed, thus closely simulating service conditions.

Routine tests carried out on every recloser include a check on its characteristics on both instantaneous and time-delay operations and on inter-tripping with other units for lock-out.

I would urge users to give all possible information to the manufacturers on these units, in order that experience may be built up in this country, not only on contact life, maintenance requirements, etc., but also on any operational difficulties which may arise in the application of the device.

**Mr. W. Gray:** The authors do not mention Petersen coils as an alternative method of dealing with transient line-to-earth faults. Admittedly this method does not deal with double line-to-earth faults, but these are very much in the minority. Nor is it of use where phase-neutral distribution is installed—a system used extensively only in the United States.

Nevertheless, where the method can be applied it affords a high degree of protection and appears to be much cheaper than automatic circuit reclosers, particularly where a large number of feeders is involved. Under what circumstances are automatic circuit reclosers economically justified?

It is not clear why the authors have adopted the construction shown in Figs. 13 and 15. The greatest demand will be for 3-phase and 2-phase reclosers; this being so, would it not be cheaper to adopt a single-tank construction using one mechanism and one time-lag device, rather than an arrangement requiring two or three tanks. Such a design would lend itself to the use of one shunt-operated coil rather than a number of series-operated coils, which should be cheaper and allow the breaking-current capacity to be increased.

Why have the authors adopted the duty cycle shown in Fig. 18?

**Mr. R. A. Coke:** The operational experiences referred to in the paper appear to have been carried out on an 11 kV system and the results would appear to justify the installation of such reclosers on a large scale. In the North Eastern Area we operate a large interconnected system, mainly at 20 kV but with some 11 kV distribution, from a centralized control room where every operation of a neutral alarm is carefully recorded and accounted for so far as possible. It is not sufficient for us to know that there has been a fault somewhere on the system and that supply may have been resumed by an automatic circuit recloser. We would require some external indication or counter visible from ground level either at the recloser or at a suitable point of supply. Is there any difficulty in this, and is there at present any means of checking the number of operations carried out by the recloser without having to de-energize the circuit?

On our system we have automatic reclosers which reclose only on earth-leakage faults and not on overload faults. The reclosers shown in the paper would appear to be operated by the fault current, and their rupturing capacity would therefore need to be higher than if they reclosed only on earth faults. Has this feature materially increased the cost?

Have the authors any experience either on a system or on tests of the operation of such reclosers designed for 20 kV?

[The authors' reply to the above discussion will be found overleaf.]

## SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 4TH APRIL, 1955

**Mr. R. Mallet:** The first brief reference to American-type high-speed reclosers was published in this country in a paper by Garwood and Websdale,* and in view of the paucity of the information available many felt that the claim for their performance was exaggerated, particularly since the price quoted for a single-phase unit was only £35.

In November, 1949, I met the late Mr. G. A. Matthews, who pioneered the development of this equipment in the United States, and I saw the units. I was impressed with their possibilities, and thereafter collected all the information I could. British switchgear manufacturers who were approached regarding their manufacture were not enthusiastic, since supply engineers generally required switchgear with a minimum rupturing capacity of 150 MVA. The limited rupturing capacity of these reclosers is very little handicap in practice, however, and they will probably be suitable for use on at least 95% of the route mileage of the 11 and 6·6 kV lines in Great Britain. At one stage it was felt that the absence of fuses with suitable characteristics would prevent their use, but by 1951 these difficulties had been overcome and the first prototype recloser was available.

While many of the practical difficulties have been anticipated, considerable operational experience will be required before the best open-circuit time referred to in Section 3.1 can be determined. Some maldiscrimination may also be experienced through fault currents not reaching anticipated levels.

* GARWOOD, G. T., and WEBSDALE, G. J.: "The Phase/Neutral System of Supply for Rural H.V. Distribution," *Proceedings I.E.E.*, Paper No. 817 S, September, 1949 (97, Part II, p. 281).

**Mr. J. S. Cliff:** One of the most important factors is the cost of the equipment, and I presume that this is why more emphasis appears to have been placed on the scheme using fuses. This imposes severe technical limitations. Since the recloser must clear the circuit before the fuse begins to melt, the moving parts must obviously be as light as possible, and this naturally restricts the currents which can be handled. Table 3 shows that these are comparatively small. On the other hand, the fuses must have as long a time-lag as possible, and this necessitates a greater amount of metal in the element, which will have an adverse effect upon the breaking capacity. A new British Standard for h.v. fuses is about to be published; will the fuses used comply with the very stringent test clauses proposed?

Because of the limitations of the apparatus, the layout of any system must involve very careful consideration if satisfactory operation is to be obtained. Fig. 6 indicates that at least 2 miles of line is essential before the short-circuit current is sufficiently reduced to make it safe for a recloser to be installed. Series reactors are shown in the test circuit (Fig. 10); are similar reactors used on actual supply systems?

It is clear from Table 8 that, to obtain a reasonable range of current for satisfactory co-ordination, the normal current rating of the fuse must be large compared with that of the recloser. In the typical layouts shown in Fig. 3 the 50 amp recloser is followed by 75 amp fuses, and the 15 amp recloser by 30 amp fuses. Since there are several circuits, it is clear that the maximum current passed through the fuses must be much less than their normal current rating, otherwise the recloser would be burnt out. The

minimum operating current of the recloser is twice its rated current, so that protection is given only for appreciable overloads. Since the transformers are solidly connected to the lines, it seems probable that on internal faults considerable damage could be done before the fault current becomes sufficiently high to operate the recloser or fuses.

Presumably the minimum fault currents shown in Fig. 3 are the earth-fault currents. I doubt whether such high values are always obtained. In recent discussions on the h.v. fuse specification, C.E.A. representatives stated that under dry conditions earth-fault currents were often insufficient to melt the fuses. In such cases it would seem that fallen lines would remain energized and be a danger. How does the authors' scheme deal with such cases? Does it comply with the Supply Regulations?

The scheme using sectionalizers appears to offer the opportunity of greater flexibility, since the time delays can be correlated more easily. This should enable reclosers with greater breaking capacity to be developed. Are schemes using sectionalizers being used, or are they too expensive?

**Mr. F. K. Fowkes:** On a system which has some 200 miles of 12 kV line in circuit there are a number of reclosers which have been in service for 15 years and have individual records of some 2000 operations with one set of contacts. These reclosers are orthodox oil switches, and for ten years (during the war) they operated with the same oil in the tanks, which shows oil-carbonizing troubles to be exaggerated.

The paper shows the jumpers to the reclosers to be parallel and close together; my experience suggests that, if discontinuities are introduced in the line construction, trouble from lightning will ensue and the reclosers will suffer damage. Care must be taken to introduce the reclosers into the line in such a man as to preserve impulse levels.

**Mr. H. M. Fricke:** In the past the requirements for fuses ha been for fast operation. A new requirement has now arisen f a fuse which was sufficiently slow in operation to allow the hig speed recloser to carry out its function. Satisfactory designs f slow-melting fuses of the expulsion type have been produced.

**Mr. E. V. Hardaker:** The application of any one of the schem described would result in a greater area being subjected transient interruptions, and I should like to know the avera apparent-power coverage per recloser unit anticipated.

The scheme incorporating reclosers of the hold-closed type h the advantage of simpler co-ordination, although it requires extra fuse. Is there not a further advantage in that it will n require to be manually closed after the clearance of a faul With the lock-open type there is a possibility of the circu breaker having to be manually closed at a time when it is becomi due for maintenance, and when there is a likelihood of carb having collected on insulating surfaces.

**Dr. D. H. Walker:** Presumably there are a number of sing phase motors connected to rural lines which are used f driving milking machines, separators, etc. What happens these machines during the 30 sec interval between the openi and reclosing of the automatic circuit recloser?

**Mr. T. G. D. Wintle:** Could the authors give some informati on the variation of the time-lag due to change in the ambie temperature altering the viscosity of the oil? Oil is not a goo thing to use for this purpose; to achieve the close discriminatio required implies a pneumatic type of device without any slidi parts, using air as the time-lag medium.

## THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

**Messrs. G. F. Peirson, A. H. Pollard** and **N. Care** (*in reply*): We appreciate Mr. Flurscheim's remarks and entirely support his views that we cannot assess the value of continuity of supply in terms of energy lost. The fact that continuity of supply can be assured has resulted in consumers taking an electricity supply for increased requirements where alternative sources of power might otherwise have been adopted. On this basis, capital investment could well be justified if it could be shown that reduced shut-downs result. The circuit recloser has this quality at a very low capital outlay. All reclosers are fitted with counters, and the self-rewinding feature should never lead to recloser failure, as simple records of the number of reclosures are available for the maintenance engineer's inspection.

Conditions may arise where the power factor of the fault is below 0·3 and this is the reason why the breaking-capacity tests were carried out in line with the requirements of B.S. 116, although many of the faults which occur may be less severe.

We cannot agree with Mr. McLean that the "unknown" faults, given in Table 1, are likely to result in reclosers running through to lock out. These "unknown" faults have caused no damage to plant, and it is quite likely that the majority of them resulted from undetected lightning transients.

Although we accept Mr. McLean's principle that the time duration of transient faults is important with fuse or circuit-breaker protection, it is not important when dealing with the effect of recloser operation, since arcs due to transient faults are suppressed during the first open-circuit time. This particular point was emphasized in our ciné-film of the transient flashover of insulators under fuse-protected and recloser-protected conditions. The impulse withstand voltage of the circuit recloser is in excess of 95 kV. Considerable thought was given to the choice of lock-open or hold-closed for the British recloser, and we agree that the decision taken was not easy; however world-wide opinion favours the lock-open type.

With regard to the sectionalizer, we feel that on rural ne works there is no justification for the extra cost as compar with fuses. Mr. McLean seems to have in mind further appl cations of sectionalizers on the more complex networks. W agree that this provides a very interesting subject, and und such conditions reclosers which count up to five or six might justified. We see the possibility of the application of this typ of automatic sectionalizing, but feel that on rural networks would be difficult to justify economically.

We would point out to Mr. White that, although 11 kV lin are now usually erected to the requirements of B.S. 1320, man lines of earthed and mixed construction exist. The results give in Table 1 are for an extensive network in which various co structions exist. There are many points where earthed met must be introduced, such as at transformer connections an switching points, so that earth faults are always a possibilit Maintenance of reclosers can be carried out by normal mai tenance staff, and we would draw Mr. White's attention to M Mallet's contribution to this discussion. The recloser is normally closed device and is therefore not suitable for th protection of series condensers, where a normally-open device required, except under short-circuit conditions.

We thank Mr. Jones for underlining the difficulties whic may be experienced with networks earthed with Petersen-coil A recloser should always prevent the blowing of fuses und transient fault conditions irrespective of the type of fault, wherea with the Petersen-coil-earthed system phase-to-phase faults ma cause an interruption of supply which would be avoided on recloser-protected network.

Mr. Woods queries the advantages obtained by the introdu tion of the "break back" feature in the time-delay-trip operation of a recloser. It should be pointed out, however, that many rura networks are protected by direct-operating a.c. trips shunted b fuses, and for this reason a characteristic for the recloser must b

obtained which provides discrimination with both relay- and a.c.-trip-protected systems. The recloser in itself must be inherently simple, but it is possible by modification of the jet to obtain shorter times for the delay trips; this has the effect of limiting the range of co-ordination, and it was felt that it was not desirable to standardize a recloser of this type.

No powder-filled fuses have been used, as the types mentioned in the paper are generally cheaper. However, no difficulty should be experienced in utilizing them in conjunction with reclosers, provided that their characteristics are suitable. The estimated full-load loss on a 50 amp recloser would be approximately 60 watts, but allowance must be made for load factor and the resulting total loss will be negligible. We agree that the smaller size of recloser might not be justified in this country; the smaller ratings, however, have been included to meet export requirements.

In reply to Dr. Golde, the simultaneous operation of tee-off and transformer fuse is classified as one "supply interruption." The total number of permanent faults given in Table 1 is correct, and includes persistent damage where known to be due to lightning. The number of interruptions set against cables, insulators, etc., are when failures of these items occur which were not due to lightning. Dr. Golde seems to have overlooked the fact that fuses, as shown in Fig. 3(*a*), operate in conjunction with a recloser. Under these conditions it is only permanent faults which cause the fuses to blow; under transient fault conditions the recloser breaks the circuit and the deterioration of both the 30 and 50 amp fuses is negligible. Duplex gaps are fitted, although this is not clear from the illustrations.

Mr. Hywel Jones raises rather a special case, and the use of a recloser on such systems would not appear desirable if the plant concerned is synchronous.

We agree with Mr. Mather that in the United States small substations sometimes consist of a transformer and reclosers only, and there may be cases in this country where similar conditions could apply. The isoceraunic level in this country does not justify the multiplicity of surge diverters used in the United States.

The expense of providing earth-fault protection on reclosers could not be justified. No statistics are available to give an exact answer to Mr. Ryland's queries, but a safe estimate would be that 90% of rural lines can be protected by reclosers having a breaking capacity of 50 MVA. Provision of one high-speed and one time-delay trip operation only would not materially cheapen the recloser, but would limit the co-ordination range.

Mr. Larkum's example emphasizes the outstanding advantages to be obtained by the use of reclosers. On instantaneous trips very limited discrimination can be obtained between reclosers in series, but with the design put forward there is adequate discrimination on the time-delay trips; thus it is not necessary to vary the numbers of reclosers, and accurate discrimination can be obtained by using reclosers of varying current ratings.

In reply to Mr. McNeill, tests which were undertaken in the Midlands did include the type of American recloser, using a hydraulic mechanism for sequence control. With this type of mechanism, however, oil contamination can interfere with satisfactory sequencing.

In our view the N.E.M.A. tests are not representative, in that they demonstrate a performance which is inconsistent with the service requirements of a recloser. The duty of a recloser necessitates at least two sets of tests to demonstrate the suitability for service operation, namely breaking-capacity tests and electro-mechanical endurance tests. As shown in the paper, it is considered that for the breaking-capacity tests a series based on B.S. 116 will show its ability to interrupt fault current.

It is also important to carry out electro-mechanical endurance tests as described by Mr. Gaze, and these will demonstrate the ability of the recloser to withstand many thousands of operations under conditions similar to those occurring in service.

The statistics collected by Mr. Shackleton should be comparable with those given in the paper, since counters were not used to obtain this information, and a fault requiring several reclosures is classified only as one incident.

In answer to Mr. Whibley and Dr. Walker, with the dead-tank design of recloser put forward there is very little extra cost incurred in the intercoupling of single-phase units, and such an arrangement has the added advantage that 3-phase tripping of the h.v. system results only from a persistent fault. All transient faults result in the opening of the appropriate single-phase unit for less than one second, and the effect on the medium-voltage system will be reduced voltage on two phases for this short period. The disturbance on the medium-voltage system is so slight that both single- and 3-phase motors will continue to operate even if no-volt releases are fitted to the motor control switches.

Although we agree with Mr. Gray that Petersen-coil earthing prevents the permanent interruption of supplies, as pointed out by Mr. Jones, there are severe limitations to the use of Petersen coils; moreover, with this device there is always the possibility of danger to life. The duty cycle adopted for the recloser appears to be the one generally favoured by world opinion.

In reply to Mr. Coke, no consideration has been given to the design of pole-mounted reclosers for 20 kV. However, the recloser cycle could no doubt be applied to normal 22 kV circuit-breakers, and provided that the speed of operation on instantaneous trip could grade with series fuses, a similar system of reclosing could economically be applied to 20 kV systems.

In reply to Mr. Cliff, it is not anticipated that the breaking capacity of h.v. fuses would be seriously reduced by slow-speed elements. Various designs are in use and the reduction in breaking capacity will vary. Series reactors are incorporated with the test circuit merely to simulate varying fault conditions; they will not be used in service. It is agreed that on rural networks phase-to-earth faults vary considerably in magnitude. However, the recloser will operate at fault currents down to twice its rating; thus the protection obtained is generally better than that with other types of protection.

We agree with Mr. Fowkes that every effort must be made to retain impulse levels at recloser positions. It has recently been decided that reclosers should not have their tanks earthed, and this should improve conditions generally.

Although, as Mr. Hardaker states, a recloser is used to protect an area greater than the present system protected by fuses, transient interruptions are not in themselves serious and permanent interruptions can be avoided. Even when based on the full-load current a 50 amp recloser should cover a network having a maximum demand of 1 000 kVA which, allowing for diversity of load in rural areas, would be equivalent to a considerable length of network. We think that closing a recloser manually after the clearing of a fault is always to be preferred to the replacement of fuses, which would be necessary if hold-closed reclosers are used.

In reply to Mr. Wintle, although certain variations in time of operation occur, owing to change in oil viscosity, they are negligible in the instantaneous operation and involve only a slight increase on the time-delay trips when the oil in the recloser is very cold. It must be remembered, however, that reclosers are generally carrying load at such time, and the current in the solenoid operating coil will to some extent offset the change in ambient temperature. Even were this not so, the tendency is to improve the co-ordination with fuses.

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# THE ELECTRICAL ENGINEERING INDUSTRY IN THE POST-WAR ECONOMY—

By G. L. E. METZ, M.I.Mech.E., Member.

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SUMMARY

The paper considers the electrical manufacturing industry, its contribution in terms of production, exports and employment, and it comments on the use the industry is making of the resources at its disposal; the paper is in three main parts. The first outlines the general economic background and the position occupied by the industry in the general pattern of trade. The second refers to general problems affecting production, research and export, and comments on the objectives towards which the industry is progressing. The third deals with the strategy for achieving these objectives and for making the best use of the resources at the disposal of the industry.

## (1) INTRODUCTION

In 1946 the author[1] attempted to outline some of the economic problems facing this country and to define that part of the problem which might be expected to become the responsibility of the electrical industry. The author dealt with the contribution made by the industry in terms of production, exports and employment, remarked on its growth and suggested that the situation might with advantage be reviewed at appropriate intervals.

Since that time almost every Presidential Address to The Institution has stressed the fact that we live in an age of specialization and also the importance of stopping occasionally to see where we are going and what we are achieving. It is difficult to believe that these references would have been made had there not been underlying feelings of disquiet at the lack of cohesion that at times characterizes the industry and disappointment with the progress of the national enterprise as a whole. Those who have read Sir Henry Tizard's thoughtful and inspiring Messel Lecture[2] in 1952 may feel that they have found there a clue to these vague feelings of disquiet. He suggests that the strategy of industry has gone wrong largely as a result of failure to keep its objectives in view, and as a result it has not used the resources at its disposal effectively.

For several years our efforts have failed to produce a stable and sound economic position, and this, probably more than anything else, is responsible for the feeling that somehow things have gone wrong. For this reason no apology is necessary for introducing, for a second time, a subject that causes us to withdraw temporarily from the contemplation of the engineering sciences to consider our objectives and the strategy for attaining them.

## (2) ECONOMIC BACKGROUND AND POSITION OCCUPIED BY ELECTRICAL INDUSTRY IN GENERAL PATTERN OF TRADE

### (2.1) Economic Background

Seventy years ago Great Britain bestrode the world like a Colossus—the leading industrial nation with a vast empire to take her manufactured goods, and a productivity and a standard of living superior to that of any other country. To-day, great parts of that Empire have acquired Dominion status with important and thriving industries of their own, our output p man-year has fallen from its leading position (Fig. 1), and o share of world trade has of recent years been falling. Since t war the pages of history have been turning swiftly, new patter

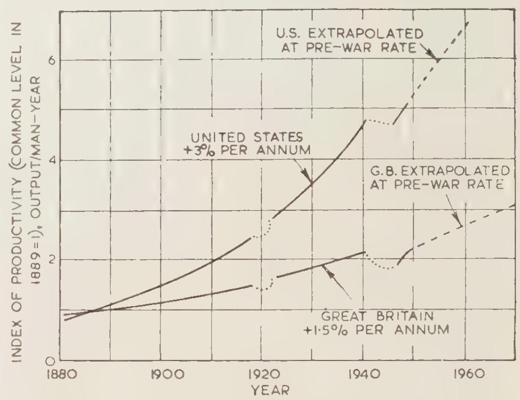



**Fig. 1.**—Indices of industrial productivity (output/man-year) f Great Britain and the United States, obtained from Reference 3.

of industrial activity are being woven and millions of people the under-developed countries are on the march towards high standards of living and towards the development of their ow resources of material and labour. The areas making the mo resolute and aggressive efforts to progress include those whi seem to have discovered how to mobilize their resources of labo and direct them towards the achievement of an objective whi they consider to be worth working for. It is significant th this has in many cases been done by psychological influenc which seek to direct the attitude of mind with which peop approach life and their everyday work. Unfortunately the grow and wider distribution of knowledge which has made th progress possible has not been accompanied by greater unde standing.

Instead of the world becoming a friendlier place in whi neighbours freely exchange their surpluses, we see on ma sides the desire—more suited to a less-enlightened age— preserve national, social and economic autonomies and to clo the doors to the exchange of ideas and of merchandise. Th makes it particularly important to bear in mind our positio relative to that of other countries, to take account of the rap increase in production by our competitors and to recognize t difficulty of acting as the workshop of a world in which eac country wants to have a workshop of its own.

This trend is bound to create problems for us, because w have few natural resources in the form of raw materials, a prosperity depends upon our ability to convert imported ra materials into finished goods which other people want. F some years now we have imported more than we have export in the form of finished goods, and if the present standa

of living is to be maintained there must be a great and rapid increase in production and in the efficiency with which we use the resources at our disposal.

The Economic Survey[5] of 1952 endorses all these remarks. It refers to the difficulties which have to be faced, and outlines the progress that has so far been made toward bringing income and expenditure into balance. At present we are living within our means, but the outlook is uncertain because of the limited reserves at our disposal and will remain so until by increased production and exports we have built up an adequate reserve. For this reason the nation has been exhorted to take a larger share of world trade, to produce more and export more and to rearrange its pattern of trade so that a greater proportion of exports go to dollar account and non-sterling countries. The driving force for this expansion can only come from industry, and this has a special importance for us because the engineering and metal-using industries together account for nearly 44% of all exports. Furthermore, the electrical industry, together with electricity supply, is generally regarded as one of the keys to greater and more efficient production in other exporting industries.

### (2.2) Contribution made by the Electrical Manufacturing Industry

Progress in the production, exports and employment of the electrical manufacturing industry during the last few years (Fig. 2) gives good cause for satisfaction. Production has

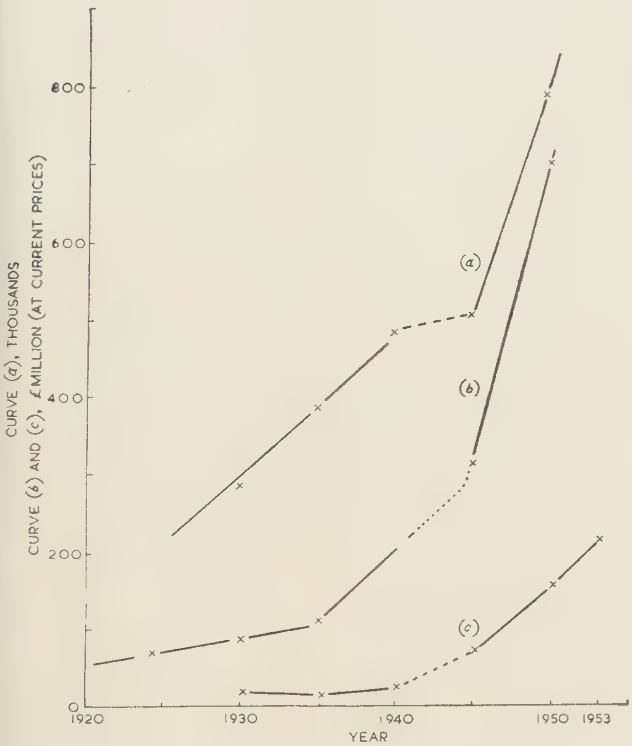



**Fig. 2.**—Production, employment and exports of the electrical manufacturing industry, obtained from Reference 6.

(a) Employment (includes electricity supply).
(b) Production.
(c) Exports.

gone racing ahead of many other industries and is still increasing faster than the national income, thus showing that electricity and electrical labour-saving devices are taking an increasingly larger part in our everyday life. But this is not the whole story, and if we consider how the purchasing power of sterling has fallen since 1938 (Fig. 3) we obtain some idea of

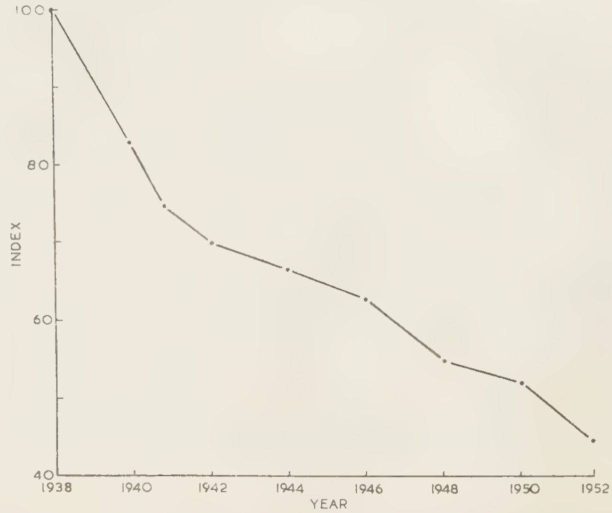



**Fig. 3.**—Fall in purchasing power of the pound sterling, obtained from *The Economist*.

the extent by which our achievements have fallen short of our objectives. The great upward surge in production and exports we are accustomed to see dwindles to a more pedestrian rate when the fall in the value of sterling is taken into account (Fig. 4).

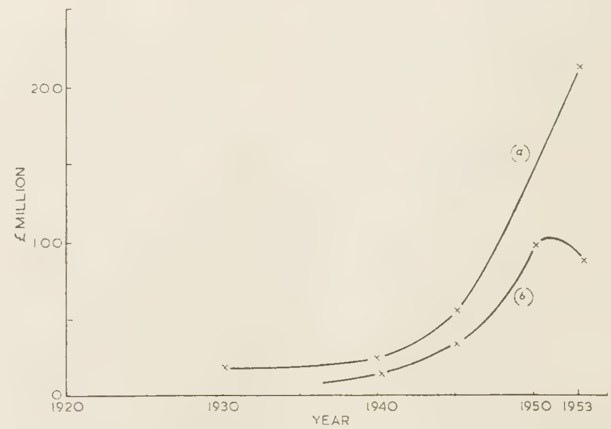



**Fig. 4.**—Exports of electrical goods and machinery.

(a) Exports at current prices.
(b) Exports adjusted to account for the fall in purchasing power of the pound sterling.

Nevertheless the annual increase in production is still high compared with the annual increase in the national income and with the annual increase in the use of such basic raw materials as sulphuric acid and alkali of 2–3% (the latter are generally regarded as indices of industrial production).

Exports have also increased since the war, and in 1952 reached the remarkable figure of £220 million. While the total production and exports of all industries together may not have been as high as circumstances demand, the performance of the electrical manufacturing industry in these spheres has been quite remarkable. Nevertheless, the fact remains that no matter how ingenious we may have been, or how hard we may have worked as individuals, the results of all industries taken collectively for the whole country have been insufficient to build up adequate reserves. It is therefore necessary to consider whether the industry can do still better and whether it can do more to help other industries to increase production and exports.

## (3) PROBLEMS AFFECTING PRODUCTION, RESEARCH AND EXPORT, AND OBJECTIVES OF THE INDUSTRY

### (3.1) Production

The problem of increasing the production and export of United Kingdom manufactures is a difficult one. There has been progress since the war, but it has not been sufficient to reduce materially the gap between production here and that in the United States. The solution depends largely upon increasing productivity, i.e. the production per employee. In the electrical manufacturing industry the annual increase in production has gone racing ahead of many other industries, and it might appear that there remained no more heights to conquer. But this is not the case; side by side with the increase of production has gone the increase in employment, so that while production may have increased rapidly, production per man-year has increased at a much more modest rate. It would seem to have averaged little more than the general run of all industries taken together (see Fig. 5).

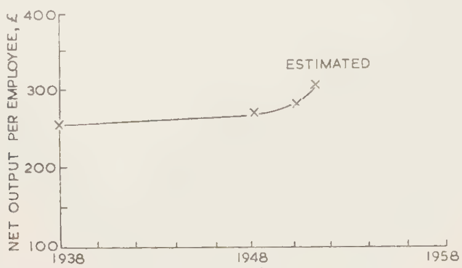



**Fig. 5.**—Value of net output per employee (adjusted to allow for the fall in the value of the pound sterling).

It is a modest figure for an industry in which there has been very considerable capital investment, which includes some of the most efficient plants in the world and to which other industries look for help in solving their own productivity problems. The last few years have seen great advances in the development and application of simpler and more effective techniques which were intended to pay for their installation by increased productivity and by the release of labour for other and presumably more important work. In many cases the money—or what is perhaps more important, the resources it represents in terms of materials and human effort—has been spent without the expected savings of labour or the increased productivity being fully realized. It may well be asked where these benefits have gone. The answer is that they have, to a considerable extent, been used to provide easier conditions for employees and to reduce the number of working hours. (More has been done by machines, and less by human effort.)

It is not widely appreciated that the results of increased productivity can be taken in the form of more goods or more leisure, and in this country—as in North America—considerable importance is attached to the latter and not so much to the former, which does not, without explanation, result in any noticeable benefit to the people actually concerned with the production. It is not only that productivity in this country has not risen fast enough since the war, but the results have been, and are being, taken to a considerable extent in the form of easier working conditions and shorter working hours.

#### (3.1.1) Productivity.

It has been known for some time that productivity has been a good deal higher in the United States than in this country, and that our progress relative to other countries with which we have to compete has not been spectacular. A large number of teams from different industries have visited North America to find out why this is so. Nearly all of them have commented on the amount of capital equipment and power at the disposal of each worker there and the enthusiasm with which all ranks apply any new or improved process that will increase the quantity of goods that are made. This probably explains the prevalent view—not always qualified by the fact that Americans pay about three times as much for each man-hour as we do—that, if the capital equipment and power at the disposal of each worker here could be increased to that in the United States, productivity in this country would rise as quickly as it does there.

It is by no means certain that the answer is as simple as that. The advantages of more machines and power, the application of time study, the streamlining of processes, the use of incentives and so on have been known and practised here for many years.

The question that has perplexed so many is why the application of this knowledge here has not resulted in the increased productivity that many feel would have resulted in like circumstances in America. A great deal of thought has been given to this question. For a time it was thought that productivity could be increased by exhortation but that has not achieved very much; incentives of one type and another have been tried without unqualified success. Then it was thought that productivity could be increased by the use of more and better machines, but that will not help without the will to use them. Slowly the conviction has grown that unless ordinary men and women are convinced of the virtue and necessity of producing more, more will not be produced. The question to be asked now is not why we do not produce more, but why we do not want to produce more. These words have been quoted from the *Economist*, and they state the situation as it appears to a distinguished observer who is nevertheless detached from the immediate sphere of engineering and manufacture.

This view appears to be shared by other important groups such as the British Productivity Council, the British Institute of Management and the Trades Union Congress. There is thus an influential body of opinion which recognizes that the problem of increasing productivity cannot be solved merely by the addition of capital equipment and power. There have also been important developments in certain sectors of industry, one of the most promising being that introduced by Imperial Chemical Industries and known as Work Study. When it was first applied to a section of the chemical industry the annual increase in productivity averaged about $1\frac{1}{2}\%$. This has increased to $8\%$, a great part of the improvement being attributed to the application of the principles of Work Study. These principles aim at making the most effective use of plant and human effort. It is not so much that they use techniques that have not been used before as that they apply knowledge already available in a new way. They are strictly concerned with physical conceptions based upon an arbitrary unit of work, in terms of which the work content of a wide variety of processes can be expressed. But lying behind these physical conceptions is the thought that the effective use of capital equipment and power depends much more than is customarily supposed upon psychological factors.

#### (3.1.2) Psychological Factors.

Many people believe that the conventional approach to the problem of increasing productivity is quite out of tune with the times. They feel that advances in knowledge during the last forty years have removed all the technical barriers to efficient production. But while these wonderful advances in scientific and technical knowledge have been taking place, progress in the application of it to worthy causes has hardly advanced at all. As a result the knowledge so laboriously gained cannot be fully translated into action because the wisdom which alone can

provide a sense of direction is lagging behind. It almost seems that, now we have arrived at a point where technical knowledge could provide so many of the things we all desire, the power to provide them still lies outside our grasp because the will to turn these possibilities into reality is lacking.

It is these circumstances that make psychological and human factors of such vital importance, and this particularly applies to the engineer because all his skill and efforts become ineffective unless society is prepared to apply and use the aids to production that advances in technical knowledge have made possible.

Whenever psychological problems of this kind arise they bring with them an acute awareness of the limitations of human understanding. In the presence of so many imponderables there is a tendency to dismiss the subject as beyond logical solution and outside the realms of practical application. If this is so it seems that the result of all the advances in the technical field will merely be to relieve mankind of the need to work, and its possibilities for bringing the good things of life within the grasp of many will be lost. But I believe that these psychological difficulties, like technical ones, will be overcome, and that the possibility of taking a step in the right direction may be nearer to hand than is generally realized.

Fifty years ago a man had no difficulty in seeing the benefits conferred on his fellows as a result of his individual efforts. He could readily see, and so could his neighbours, what happened when he did his job properly, and what is perhaps more important, what happened when he did not pull his weight.

To-day, modern society has become so complex that it is the exception rather than the rule for man to be able to see the benefits his individual efforts bring to the community. In most cases he works as one of a team; his efforts are merged with those of others, and if it is not a good team all his efforts to help can be frustrated. As a result the individual in industry no longer has a clear objective. Directly the application of knowledge raises the standard of living to a level that ensures the necessities of life, i.e. directly the battle for survival is won, one of the prime factors which gives life its purpose steps out of the arena. In the absence of some worthwhile objective to take its place frustration and aimlessness are liable to step in.

There is no obvious reason why an employee should be interested in adopting new machines unless he feels that they will give him the things he wants. Neither is there any obvious reason why anyone should invest in capital equipment and power merely to enable people to lie in bed on Saturday morning. To get the most effective use of resources there must be a common objective which people feel is worth working for. It is not sufficient to say that new machines and processes will do twice as much as the old ones without explaining the advantages they offer to the employee and to the community he serves. In these days, most improved processes involve the use of power and plant, the advantages of which can only be explained by technical men who themselves are aware of the ways in which these new tools can help society. It is necessary to look beyond the engineering terms in which the merits of machines are usually expressed to the final advantages they confer on the community as a whole and then to explain to each member of the team that what is good for the beehive is also good for the bee.

If we look at the electrical-engineering industry as a microcosm of industry as a whole we can see how difficult it is to discern its objectives. The habit of referring in a language of our own to the tools we make for use in other industries has resulted in an industry in which it is exceedingly difficult to find either an objective or a sense of direction in which to progress. We regard a more efficient method of generating electricity as a decrease in the number of pounds of steam per kilowatt-hour and not as a means of bringing warmth and comfort into the homes of many who could not otherwise afford them, and so on. Yet it can hardly be said that the engineer (with the power to provide, by the application of technical knowledge and skill, the necessities and amenities of life to a world inhabited largely by very poor people) has no objective. If productivity in our own and other industries is lagging behind, I suggest that the reason is not so much because the ways of increasing it are not known, as because they have not been presented in terms that can be generally understood.

The fact remains that, whether people want more goods or more leisure, they can only get them by increased and more efficient production; and this can only come from the use of more and better machines and devices and from the will to use them.

(3.1.3) **Demand.**

If we look at world trade (all commodities) between the years 1925 and 1951 (Fig. 6), it can be seen that production and


Fig. 6.—Movement of world production and international trade (all commodities), 1925–51 (1929 = 100), obtained from Reference 8.

——— Production.
– – – – International trade (volume).

exports have increased remarkably since the war in spite of severe restriction of imports and to a lesser extent of exports. This is due to some extent to aid from America, which between 1945 and 1951 amounted to nearly 10% of the international trade of that period, and perhaps to a greater extent to the existence of a backlog of demand built up during the war years. It was not due to any prescience on our part. Although the trend in production and world trade has for many years been upward, the rate of rise, although steady, has not been large—probably no more than 2–3% by volume—and is quite insufficient to absorb the rapid and large increase in exports which our present circumstances demand.

Since the war, the demand for electrical plant, equipment and appliances has far exceeded the capacity for producing it. As a result production has steadily increased year by year. But there are signs that production is overtaking demand as the ravages of war are repaired and as a result of the reappearance of

Germany and Japan as competitors. It seems inevitable that our share of international trade will fall unless we can find some means of combating the very strong competition we shall encounter from these countries. It is as well to remember that the period of almost unlimited demand enjoyed by the industry since 1939 is not the normal state of affairs, and is unlikely to return during our lifetime unless, of course, there is another war.

Against this background the call made in the Economic Survey for more production assumes a different complexion, and it seems clear that it means something different from making two articles where one was made before. This increased production has to be disposed of before it can contribute to our economic welfare, and that is in many ways a more difficult problem than increasing production. It is also important to bear in mind that, if Great Britain takes a larger share of world trade, competing countries will be left with a smaller share, and to the extent that they are customers for some classes of goods as well as competitors for others, that will not necessarily be a complete solution of the problem. Again, if by some means the selling price of electrical plant and equipment could be reduced by one-half, it would be necessary to export twice as much to obtain our present income from oversea. Like the Red Queen in *Alice Through the Looking Glass* we should have to run twice as fast in order to stay where we are now. It seems, then, that the problem is not, as it is so often expressed, merely one of making more things more cheaply, nor is it solely one of producing two things for every one made before or of taking a larger share of world markets. That does not mean that there is no need for more or cheaper production or that it does not matter whether we increase exports or not, but it indicates very clearly that our objectives are neither so obvious nor so clear as they may at first sight have appeared. There are certain rather vital balances which determine the optimum levels of trade, production and price and which deserve more attention than they have so far received.

### (3.2) Research and Development

The United Kingdom spends annually about £200 million on research and development—a somewhat nebulous term, of which roughly 12% is contributed by industry and the balance by the Government. Government expenditure covers a variety of projects many of which are of warlike character but which nevertheless have, or may eventually have, important civil applications (e.g. atomic energy). This compares with an annual expenditure in the United States of some £1 000 million, of which nearly one-half is contributed by industry. In short, the United States with a population about 2½ times that of the United Kingdom spends five times as much on research, and the United States industry alone spends nearly twenty times as much as the United Kingdom industry in this way.

It is easy to conclude from this that the United Kingdom spends too little on research, and it certainly appears that the contribution made by industry when taken together is smaller than it should be. But capital investment by industry which is necessary to turn the results of research to practical use has for the last few years been running at the very modest figure of £500–600 million annually. It has until recently been restricted to this figure by Government controls which have now, however, been almost completely lifted. But the incidence of taxation, high cost of capital and the effects of inflation tend to limit the capital available for investment, and particularly the risk capital required to develop and apply the results of research.

A director of one large concern that spends roughly £2½ million annually on research and £30 million annually on capacity for its application stated recently that this scale of investment was quite inadequate. Many valuable ideas arising from research could not be developed because of insufficient capital and the difficulty of spending more than £30 million annually. It has consequently been necessary to consider whether to reduce expenditure on research and transfer the staff to work of more immediate importance or to let them continue and pigeon-hole the results of their work. It seems that the allocation of our national resources as between research on the one hand and capacity for its practical application on the other needs to be kept rather carefully in the balance.

There is a fairly prevalent view, at any rate outside the engineering profession, that the eminence of British scientists in the realms of pure research is not reflected by the engineer and technologist in his sphere of applied research. Indeed it is precisely in this field that it is said that we, as a nation, are failing. We have the original ideas, but seem to be incapable of bringing them into practical use quickly enough. The general grounds of complaint seem to be that we fail to preserve a proper balance between pure and applied research, with the result that many of our best ideas are developed abroad or are not developed at all.

It has not been possible to break down the national expenditure on research by industries, but the electrical industry appears to spend annually about £5·4 million on research and development, of which about £3·3 million is spent on heavy engineering and the remainder on light engineering. Probably most of the latter is spent on communication and radio equipment. This expenditure seems large in comparison with the expenditure by the mechanical-engineering industry (£3 million) and small in comparison with the expenditure by the chemical industry (9·7 million). It represents less than 1% of the value of total output. The corresponding figure for electrical research in the United States is £70 million. It was no surprise to find that more money is at present being spent by the electrical industry on research on heavy than on light engineering. But it must be borne in mind that in nine cases out of ten it is the problems at the working level that count. Electricity is a servant, and electrical appliances, whether domestic or industrial, are mainly labour-saving devices. The importance of the profession is in direct proportion to the contribution it makes at the working level in industry and in the home, and that is where one would have expected the bulk of the expenditure on applied research to have taken place. But the fact is that it does not.

Every useful application of electricity to everyday life increases the demand for electrical appliances for electricity generating plant, transmission and distribution equipment. The same cannot be said of an improvement in, say, the efficiency of a turbo-alternator. This does not mean that research on improving the efficiency of turbo-alternators is a waste of time, but it is doubtful whether it will result in an increase in the demand for electricity, generating plant, etc. This makes one wonder whether the most fruitful field for research at a time when there is insufficient money to do all the things we should like to do is in the design of new and improved industrial and domestic appliances. That is the reverse of what we are doing now.

The problems of research like those of peace are indivisible; advances made in one direction open up possibilities in other and on the surface, quite unrelated directions, which it is very difficult to foresee.

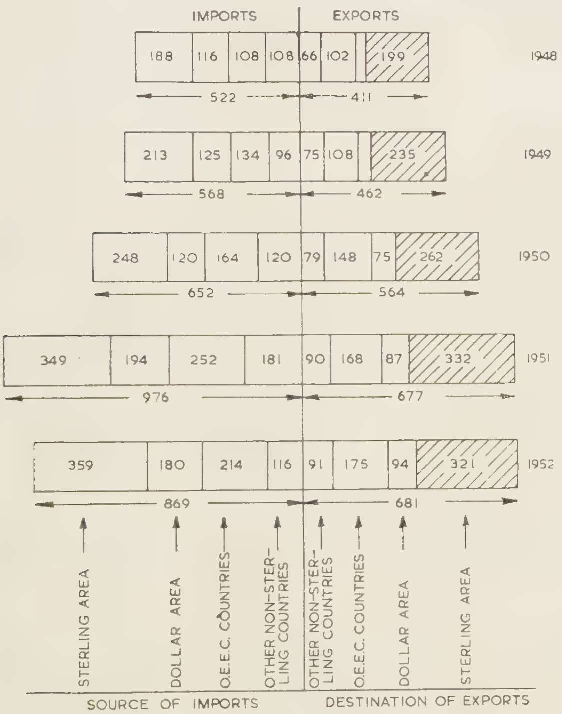
For this reason it would be of considerable assistance if there could be periodic reviews of the advances made, and some attempt made to signpost the possible fields of application. If this could be done it might lead to discussion and raise questions such as "How does this advance help me in my work?" and "Can I apply this new discovery in my specialist field?" etc.

In referring to the importance of a proper balance between the allocation of resources to pure and applied research and

e provision of capacity for its application, I do not suggest at things have got into a hopeless state. Nevertheless the nclusions which begin to emerge from this very inadequate amination of a very large subject seem to be that (*a*) the dustry is spending only a very small proportion of its turnover n research, (*b*) it is by no means certain that it is concentrating n the problems whose solution would make the largest and iickest contribution to our economy, and (*c*) the benefits of search might be increased if some means could be found of gnposting the various fields of application which may be fected and of providing for their discussion.

### (3.3) Export Trade

The oversea trade of the United Kingdom during the last w years is shown in Fig. 7. The pattern of this trade showing




g. 7.—United Kingdom trade (quarterly averages) in millions of pounds sterling.

e source of the imports and the destination of the exports is so shown in Fig. 7. The greater part of the United Kingdom ade is within the family, i.e. with the member nations of the ommonwealth within the sterling group, and in this particular ctor the balance between imports and exports is better than the other sectors. The greatest unbalance occurs in the dollar count and non-sterling sectors of trade, in which it is most portant for imports and exports to balance because the fference between them has to be adjusted by payments in gold.

The imports and exports of electrical goods and equipment ring the last few years are shown in Fig. 8. In spite of a nited Kingdom industry capable of producing the whole range electrical plant and equipment, imports in 1951 amounted to ughly £7·8 million. This may not seem much in comparison th the corresponding exports, which amounted to £193 million, t before this electrical plant and equipment could be made, it s necessary to import raw materials such as copper and uminium for conductors, rubber and cotton for insulating rposes and so on. This had to be paid for by exports before ere was any net contribution to the balance-of-payments


**Fig. 8.**—United Kingdom imports and exports of electrical goods.

position. The proportion of total cost represented by imported raw materials varies considerably with the type of equipment concerned. For electrical cables with copper conductors, cotton covering and rubber sheathing, it is possible for more than half the cost to be represented by the cost of imported raw materials; i.e. one-half of the export value of these cables is needed to pay for the raw materials from which they are made. I have taken a rather extreme case to illustrate this point, but it will serve to show that the exports of the electrical manufacturing industry, important as they undoubtedly are, do not contribute quite so much to the balance-of-payments problem as published figures might at first sight suggest. It follows, perhaps unexpectedly, that one of the most effective ways in which the industry can help to solve the balance-of-payments problem is to eliminate waste of all imported materials, particularly copper, cotton and rubber. This is a pointer to one of the problems which should rank high in programmes of research.

The pattern of oversea trade in electrical goods and appliances is not so satisfactory. This is shown in Fig. 9, and is even

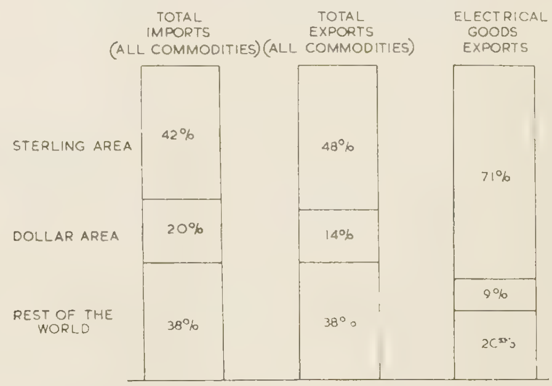



**Fig. 9.**—Distribution of United Kingdom exports.

less in harmony with the needs of the day than is the pattern of trade in all commodities taken together. The fact that most of our exports go to the sterling area was of little importance before the war when sterling was freely convertible, and indeed it was in the fitness of things that we should so far as practicable trade within the family. But at present it is essential to maintain a reasonable balance between imports and exports with each of the sectors of trade. This means that we have somehow to increase trade with the non-sterling sector in order to achieve a better balance, which entails breaking new ground so far as the electrical industry is concerned. The distribution of world trade in electrical goods is shown in Fig. 10; it will be seen that Commonwealth countries account for about one-third of the world trade in electrical goods; Europe (excluding the United

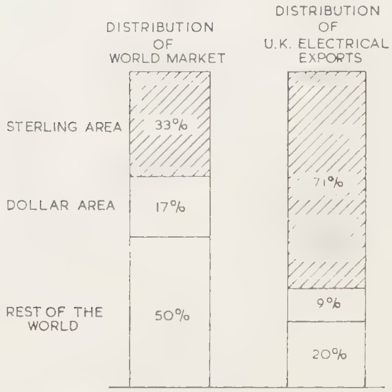



**Fig. 10.**—Distribution of world markets for electrical goods.

Kingdom) accounts for nearly one-half the world trade, and the remaining one-sixth is accounted for by South America, Eastern Group countries and the United States. At present roughly two-thirds of the United Kingdom oversea trade in electrical goods is with Commonwealth countries, which only account for one-third of world trade, and only one-fifth goes to European markets, which account for nearly one-half of the total world trade. The reason for this may derive to some extent from the adoption of different standards of performance on the Continent and in certain of the South American countries. This does not explain, however, why Continental concerns, whose goods are designed primarily to meet Continental standards, find no difficulty in transposing them in terms of British standards, whereas British concerns seem to encounter great difficulty in transposing their standards in terms of those used on the Continent. If the electrical industry is to find an outlet for a large and rapid increase in exports, it seems that it will have to look to the European and other markets, which together account for over half the world trade in electrical goods.

## (4) CONCLUSIONS

Before attempting to summarize the results of this investigation, it is important to bear in mind certain developments which seem likely to affect the problems which the electrical manufacturing industry, in common with others, will have to face in the future.

It has been said that Great Britain stands at a parting of the ways. She can by reason of her technical knowledge and skill become once again the leading nation of the world. Or if she so prefers, she can revert to the position in world affairs commensurate with a little island, with few natural resources. For a limited period we are free to choose which path she shall take. If we choose the second alternative we can sit back and watch the tide of events gently carry us back to obscurity. If we choose the first alternative our goal lies ahead at the end of a long and hard road.

The world looks for its leaders among the strong, and Great Britain as a result of grievous injuries from two world wars is still economically weak. If she is to remain great she has first to rebuild her economic strength, and for a manufacturing nation this means that productivity has to catch up and get ahead of that in competing countries. This task has a special significance for the electrical manufacturing industry and its members, because they hold one of the keys to increased productivity. On them depends to a large extent whether Great Britain goes forward or back. There are other factors peculiar to the electrical manufacturing industry which also affect the situation.

First, the next few years seem likely to bring significant chang in the source from which energy for use in industry and the ho is derived. The solid and liquid fuels which have for centur been the main source of heat—and which in more recent yea has been converted into electricity—are already giving way the nuclear reactor. There is already an awareness of pos bilities that may not be far round the corner, e.g. the producti of electricity other than by the clumsy methods of the old mi wheel or the conversion of heat by the expansion of gases turbo-alternators and internal combustion engines. The developments could well revolutionize that part of the indust which produces the presently conventional types of generati plant. In spite of these possibilities of change in the methods producing electricity, there are, as yet, no signs of any ne medium better or more flexible than electricity for the dist bution of energy or for its ultimate application at the worki level. Indeed, research into the mechanisms which contr the order and development of animal and plant life tends confirm its vital importance in the control and exercise of acti at a distance. Consequently that part of the industry co cerned with the production of equipment for the distributi of electricity and its application seems unlikely to encounter t revolutionary changes that may well affect the sector produci generating plant.

Secondly, labour is getting more expensive, and the fact th it is cheaper to hire plant than to hire labour is widening t field in which electrical labour-saving devices can be economical applied.

Thirdly, the stage has now been reached where whole factori can be controlled and run automatically without the use operating labour; where the large staffs required for such servic as the calculation of wages and P.A.Y.E. can be replaced electrical calculating and computing machines. This will resu in big savings in human effort, and will at the same time rai the problem of finding something else for the displaced labo to do.

Fourthly, from the beginning of the last war the demand f electricity and electrical devices has been increasing year year in a spectacular fashion, and has so far exceeded the capaci available. This has been due more to a variety of extern causes than to our own prescience. These favourable extern influences are passing, and the day is fast approaching when t fight for markets will be as intense as it was before 1938. Ho then, are production and exports to be increased? The sho answer is, I think, by making productivity here higher than it in the countries with which we have to compete.

Against this background, or perhaps because of it, I have n catalogued the points that have arisen in this very brief revie of a very large subject, but have instead referred to some those factors affecting the efficiency of production and th volume of exports which are deserving of special consideration

### (4.1) Factors affecting Productivity

The paper has shown that the efficiency of production cann be increased merely by the substitution of horse-power for musc power or by the addition of more capital equipment for eac employee or by the addition of labour-saving devices such a electrical appliances. On the contrary, before any really gre improvement can occur it seems that there must be a greate willingness to use effectively new methods and labour-savin devices, and a determination to act as a team rather than a isolated groups of individuals not wholly sympathetic one wit another.

There is a fairly prevalent view that this state of affairs is i no small part due to the failure of engineers to explain th advantages offered by their new machines and processes to a

those from the top to the bottom of the production chain who have to buy and use them. It is not enough to say that the new machine will do twice as much work as the old one; the operator must also be told how this will affect him and the community he serves. He must be made to realize how important he is and how he can use the new machine to overcome the national problem with advantage to us all. In this way only, it seems, can we hope to create the team spirit without which the possibilities of the new machines and appliances we design and make can never be fully realized. This situation arises from the fact that industry and the people working in it no longer have a clear objective that they feel is worth working for. The engineer has not escaped the consequences of this situation, and he also finds it hard to realize that by the application of technical knowledge he has the power to provide the necessities and many of the amenities of life to a world inhabited largely by very poor people. He has lost the habit of regarding his individual efforts as a step toward this very worthwhile objective and has lost the power to present the new tools he makes for other industries in a way that enables the people who have to buy and use them to see the benefits that will flow if only they will join us in common cause. If productivity in our own and other industries is lagging, it is not so much because the means for increasing it are not available or that there is no objective worth working for as because, in this technical age, the objective has become obscured.

It is, however, a mistake to assume that the repository of all knowledge lies in the United States. If she has learned how to increase productivity, we have learnt how to make many things better and far cheaper. We make the best ships, aero engines, optical lenses, textiles and so on, and these and many of our primary products and chemicals are the equal of and far cheaper than anything produced in the United States. In particular, we are entitled to be very proud of the fact that British transformers and hydro-electric equipment have recently compared so favourably with the best America can produce, and are now being installed there. There seems to be no reason why productivity in this country cannot be increased to the level reached in the United States.

### (4.2) Factors affecting Research

The investment devoted to research seems to be too small, and it is by no means certain that the efforts at present expended are concentrated upon the things that matter most. At a time when we cannot afford to do all the things we should like to do it would seem that research should concentrate at the working level on the development of new and improved labour-saving devices for use in the home and factory at prices that people can afford. That is not so at present. The demand for our services derives largely from the fact that it is cheaper to hire machines than to hire labour, and the stage has now been reached when whole factories can be and are being controlled and run automatically without the use of operating labour. This will release large quantities of labour, and side by side with the development of new labour-saving machines must go the search for new avenues to absorb the redundant labour. If this is not done we shall merely solve one problem by creating another.

### (4.3) Factors affecting Exports

If research at the working level results in the development of new devices, and if by increased productivity these devices can be produced at competitive prices, it seems that exports will look after themselves and the door to new markets will open of its own account.

### (4.4) General

The electrical manufacturing industry would seem to have a future that dwarfs even the spectacular advances of the last twenty years. But it also has responsibilities which, owing to the accidents of history, are in many ways greater than it has had to face before.

I believe that those in the industry will discharge these responsibilities, but I do not think they will realize all the possibilities open to them without a clear objective to give purpose and direction to their efforts and until they come to regard everything they do as a step toward its fulfilment.

## (5) ACKNOWLEDGMENTS

The information in the paper has been collected from the published sources referred to in Section 6. The author's contribution has been confined to the selection and compilation of the factors which appear to affect the destiny of the electrical manufacturing industry.

The curves and other diagrams in the paper purport to give no more than a general indication of the trend of production, exports, employment, etc. For precise figures reference should be made to the appropriate publications, and the interpretation of them must take account of the qualifications which relate to them.

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[The discussion on the above paper will be found overleaf.]

## DISCUSSION BEFORE THE INSTITUTION, 3RD MARCH, 1955

**Col. B. H. Leeson:** Most will agree that greater human effort is necessary for national progress, but few will accept the author's suggestion that our industry lacks cohesion. In fact few, if any, other industries are more effectively knit than the electrical engineering industry in a world-wide fabric whose pattern and cohesion are enhanced by the threads of professional engineers.

Thus, when the author states that "our efforts" have failed to produce a stable economic position, I presume he means "the country's efforts" for solvency. Later, he aptly describes the electrical industry as "one of the keys to greater and more efficient production in other exporting industries." This supports the generally accepted view that the nation depends increasingly for its standard of living, solvency, and security, upon the invaluable contributions that stem from the electrical profession and industry. But, although the industry is in the vanguard of the national struggle for prosperity, it cannot contribute more than the trend of general affairs in the country will allow.

The author points out that the engineering and metal-using industries account for 44% of United Kingdom exports. To this might be added the metal-producing industries, which bring the figure up to 51%, and this further emphasizes his point of the dependence of the nation on engineering.

The caption of Fig. 2 does not mention that curve (*a*) also includes 75 000 or so persons engaged in contracting. Taking into account all activities, there are probably about a million people engaged in the industry.

The average intake since the war of some 50 000 people a year into the electrical manufacturing industry is a measure of the load imposed on our educational and training facilities, not to mention their great importance.

Fig. 3 tells the tragic story of inflation, and it has no doubt led the author to express disappointment at the national effort. I share his view that it cannot be brought home too often to the individual that he cannot expect to buy more for a pound than he himself is prepared to give in personal effort for each pound that he is paid.

Later the author states, "If by some means the selling price of electrical plant and equipment could be reduced by one-half, it would be necessary to export twice as much to obtain our present income from oversea"; but that is exactly what happened in 1949 when Sir Stafford Cripps devalued the pound sterling. Our industry had to export about 40% more goods in order to earn the same amount of foreign currency. It was a poignant example of the adverse effects of inflation and the dire need to utilize our means of production more effectively and to exert more strenuous efforts.

The salient points that emerge from Fig. 4 are that the quantity of electrical exports has increased to about three and a half times the pre-war figure and that the electrical manufacturing industry is the second largest exporting industry in the United Kingdom. The author refers to net output per employee in pounds sterling, and from Fig. 5 it appears that for all industries this has increased by some 20% since 1948 and is still rising. He states that the electrical manufacturing industry has averaged little more than this. Perhaps its figures would be better if its prices did not represent such excellent value for money.[1]

It is interesting to note that the Board of Trade Quantity Index of Production for all manufacturing industries shows an increase of about one-third since 1948. I suggest that this increase could not have occurred had there not first been considerable capital investment in the supply, manufacturing, and other branches of the electrical industry, and greater use of electricity by industry in general.

With regard to productivity, the author wisely points out that its benefits can be taken in the form of more leisure or more production. I have always held the opinion that productivity is only one factor—a most important one, but only one. It is also necessary to take into account the length of time that the rate of productivity is utilized. If increased productivity arising from capital expenditure is taken in more leisure, little, if any, extra production results, and the economic position is worsened because of the additional capital charges which have to be met.

The author refers to productivity teams which have visited America. In so far as the visits and the productivity reports stimulate production by enlightening our people on what can be achieved by personal effort, they are admirable. The other side of the picture, however, is that reports which infer British inefficiency are read by our customers oversea, who naturally ask why they should buy from a country when its own reports indicate inefficiency. It is wrong to create this impression because in the products which Britain exports she is not inefficient. She is second to none and leads the world.

There is much difference between the pattern of trade and affairs in this country and in America. The United States have a large population, while we have a much smaller one. The United States have a large home market and export only about 5–6%. We export about one-third of our production and have to cater for a great variety of markets the world over.

America is often quoted as having a larger consumption of electricity *per capita* than this country. There are many reasons for this. The United States have many process plants consuming much electricity but having few operatives. Conversely we have many people engaged on arts, crafts, literature, and so on, which do not need much electricity. Comparing similar engineering works in the two countries, little disparity is to be found in the consumption of electricity per worker and their general efficiency. In short, it seems misleading to make direct comparisons between two countries whose economies and affairs differ so widely and to claim that one country leads or lags in respect to this or that.

I support the author in his emphasis on the importance of the psychological and human factors, of the will to work, and of the team spirit in the quest for individual and national prosperity—surely worth-while quests, but I must cross swords with him when he states that it is difficult to discern the objectives of the electrical engineering industry. Of all the industries that plan ahead, the electrical industry certainly does so. Its plans are made for ten years ahead; its factories are looking ten years ahead, and in the case of nuclear energy it is looking fifty years ahead. It has very clear objectives and certainly knows where it is going. Broadly speaking, the aims of the profession and industry are to extend the benefits of electricity to humanity, to contribute to the country's prosperity, and to do good in the world.

The author mentions that the demand for electrical equipment has far exceeded the capacity for producing it. To this I would like to add "and the means of paying for it." Many projects are in abeyance for this reason and because as yet our country has not been able to afford to capitalize them on a sufficiently large scale.

Few, if any, will disagree with the author that we need more research and more capital investment, but I think he understates the amount that is spent on research in the electrical industry. It is difficult to assess a figure, but I should have thought that something between £10 and £12 million was nearer the mark than the £5·4 million he mentions. Remembering the amount of research that is being done by the Government—and to which industry contributes a large sum through taxation—the total amount spent in this country on research and development is

orobably larger than is generally assumed. I suggest that the elative disparity between the amount spent in America and here s not as great as may appear at first sight.

The author has spoken of the slowness with which this country as "cashed in" on her scientific discoveries, and he has cited an example in the chemical industry. But conversely, I would cite "Terylene" as an example of British pioneering. Since he paper was written, the chemical industry, the electrical ndustry and others are involved in the recently announced ational programme for the development of nuclear energy in he form of electricity—a programme representing a worth-while objective with far-reaching prospects at home and oversea.

The author appears to suggest that research on electricity-consuming devices should be given preference to that on plant or the production of electricity. Surely both are complementary nd essential for progress in the conservation of coal. During he last 50 years, despite the increase in population and in the tandard of living, the home consumption of coal has remained ubstantially the same. This is mainly due to electrification and he more efficient utilization of coal in power stations. Research on boilers and turbo-alternators since the war has resulted in considerable increases in thermal efficiency, and units of 30 MW nd 60 MW have given place to 120 MW units, and now to 200 MW units.

Such progress represents a yearly saving of millions of tons of coal for the same amount of electricity. The recently nnounced electrification of railways will also effect considerable economies in coal, while complete electrification would save ome 10 million tons a year.

Fig. 7 presents a clear and instructive picture of the country's xport trade, and Figs. 8, 9 and 10 give interesting breakdowns. However, I do not agree with the author's criticism about xporting principally to our own family, as though this should ot be done. Every country has its own traditional markets, nd exports are bound to go that way. Of course, I agree with im that our task is to increase our exports to the dollar area, nd indeed every effort is being exerted by the electrical manufacturing industry towards that end. But we are up against reat odds. The author refers repeatedly to the question of rice, but in reality it is primarily a question of whether the dollar ountry wants our goods or not.

Take America for example, she does not want our electrical quipment, and we are up against the "Buy American" Act, he effect of which is that American concerns are not allowed o accept a tender from this country as a foreign supplier nless it is 10% (originally it was 20%) below the lowest American tender. Conversely she does want to buy our whisky o the value of £21 million a year. The same applies to textiles aving exotic appeal, for appeal often outweighs price.

Now look at the other side of the economic picture. The United Kingdom imports £42 million worth of American obacco. Is it good business for the electrical manufacturing ndustry to strive for exports to the United States, thereby ncurring financial burdens owing to the cut-throat competition nder the "Buy American" Act? Why not adopt the direct lternative of reducing our imports of tobacco from the United tates, which would alleviate appreciably the dollar situation?

This brings me to the author's conclusion in Section 4, the pening comments of which represent a wise and statesmanlike ppreciation of where Great Britain stands. I agree with him hat the country has a choice to make. If we choose more work e can be prosperous. We must be ready to meet intense oreign competition, such as that from Germany and Japan. o do this and to improve the purchasing power of the pound, e may be obliged to introduce longer utilization of our production facilities, for example, by dual-shift working. For, when everything has been done to improve productivity and further increase in total production therefore becomes marginal, how else can capital charges and overheads be spread over a greater output of goods in order to reduce their cost and price? Would not dual-shift working also economize in the capital outlay needed for new factories for a given output?

Like the author, I am convinced that the next half century will see more spectacular advances in the development of the electrical industry than there have been in the past. In the coming years the electrical industry will play an increasingly important part in the national objectives of saving resources, creating capital, increasing production and developing world trade, and of other ways by which the peoples of the Commonwealth can prosper.

**Mr. H. J. Beard:** British engineers in conjunction with British capital have played a vital part in establishing our present oversea trade. However, two world wars have substantially reduced our capital resources, and the initiative in maintaining our oversea trade now rests heavily on British industry. In this work the consulting engineer plays a significant part in continuing to provide the export of technical services, which have made such a significant contribution towards establishing the existing world market for British goods.

The Government are very conscious of our export position, and one of the more important reasons for the introduction of the nuclear power programme is to assist us to retain our position as a leading industrial nation. The White Paper refers to the part which consulting engineers will play in training staff and assisting with the design of these nuclear stations. By the construction of schemes at home, consulting engineers obtain experience which is invaluable in their oversea work. Furthermore, it provides a shop window for prospective clients from oversea. The first major oversea railway electrification scheme was largely a result of the politicians and railway engineers being able to come to this country and see at first hand the pioneer suburban electrification on the north-east coast.

The author refers to the contribution of the electrical industry to research. In some respects the responsibility for carrying out research rests as much with the purchasers as with the manufacturers. During the last few years the Central Electricity Authority has embarked upon an impressive programme which includes turbines and boilers of considerably greater capacity and higher steam conditions than those previously installed. To some extent this plant can be regarded as experimental, but it will play a very significant part in encouraging oversea customers to come to this country for their new power plants. I hope that the C.E.A. will actively continue its progressive research policy.

The author has suggested that we should concentrate more research on domestic and industrial appliances. Last year our domestic sales of electricity amounted to some 1 400 kWh per consumer. The potential domestic load is well illustrated by the sales campaign in Cape Town, which during the last 25 years has raised the domestic consumption to 5 000 kWh per consumer. The campaign has four principal features:

(i) It is a hire-purchase scheme, and the capital outlay has to be repaid between two and four years.

(ii) All appliances sold under the scheme have to be approved by the Electricity Department.

(iii) The Council provide free maintenance on all appliances for the first two years.

(iv) The Council provide free and assisted wiring schemes for both existing and new premises.

On the results achieved at Cape Town we have a potential domestic load of about 50 000 million kWh per annum, which is not very much short of the total sales of electricity by the Area Boards in this country last year.

**Mr. R. Krzyczkowski:** Whilst agreeing with the conclusion that increased productivity must be regarded as the main possible

way of improving our competitive status, it is necessary to bear in mind also that there are several factors beyond the control of the electrical export industry.

In the production process we always combine two factors, i.e. labour and capital. Unfortunately, the regulation of their prices lies mostly outside our industry.

Let us consider labour first. From the point of view of international competition, in the United States and Great Britain hourly labour rates trebled between 1938 and 1950. As the pound-to-dollar rate of exchange depreciated by 40% after the devaluation in 1949, Great Britain acquired a strong competitive position.

In Germany low wages corresponded to low productivity after the war. They doubled within the period 1938–54, and although the Deutschmark has now appreciated to a value of 12 to the pound, there is still a margin of some 10% in favour of Germany. Thus, in 1954 our labour costs in general were lower than the American ones by some 40% and higher by 10% than those in Germany. Unfortunately, labour costs are increasing rapidly. The index increased by 5% in 1954, and, according to various forecasts, it may be 6–7% higher again at the end of 1955.

Also capital costs rise. Judging from the experience of 1954 and from forecasts based on detailed analysis of trends of supply and demand, the basic materials index is likely to increase by anything from 10% to 12% between now and the end of 1955. Finally, it seems reasonable to expect that salaries will increase proportionally to wages and that current financing, true depreciation and obsolescence costs are also to increase by some 10%.

These increases are summarized in Table A. Factory 1

**Table A**

Estimated Increases in Production Costs, 1955

| Production factor | Expected rise | Factory 1 | | Factory 2 | |
|---|---|---|---|---|---|
| | | Proportion of (1) in production costs | Resultant increase in production costs | Proportion of (1) in production costs | Resultant increase in production costs |
| (1) | (2) | (3) | (4) | (5) | (6) |
| | % | % | % | % | % |
| *Labour* | | | | | |
| Wages .. | 6·7 | 50 | 3·5 | 20 | 1 |
| *Capital* | | | | | |
| Raw materials | 10–12 | 20 | 2 | 50 | 5 |
| Finished materials bought .. | 8 | 15 | 1 | 10 | 1 |
| *Overheads* | | | | | |
| Salaries .. | 6–7 | 10 | 1 | 5 | 0·5 |
| Finance, etc. .. | 10 | 5 | 0·5 | 15 | 1·5 |
| Total .. | | 100 | 8 | 100 | 9 |

represents a plant employing a good deal of labour, such as a radio- or telephone-assembly factory. Factory 2, on the other hand, shows a subdivision of production costs for a heavy electrical-engineering plant. The conclusion in both cases is that in 1955 we can expect a rise in our own production costs of between 8% and 9% owing to factors outside our control.

Even now our exports are not always competitive from the point of view of price. Hence, with increasing foreign competition and a constant rise in productivity in the United States and Germany, it may be difficult, if not impossible, entirely to pass these increases on to our foreign customers.

It may be concluded that this 8 or 9% increase in production costs is the figure representing the desired minimum target for productivity increase. It seems very high, but I note that it was actually achieved in Imperial Chemical Industries, and I understand that this was mainly due to the introduction of work study.

**Mr. H. I. Scholar:** In Section 4.3 it is stated: "If research at the working level results in the development of new devices, and if by increased productivity these devices can be produced at competitive prices, it seems that exports will look after themselves and the door to new markets will open of its own account." What has been happening since the war has little to do with export. The chairman of one of the most successful radio companies in this country recently stated, in connection with the building up of an export organization, "We have exported a lot, but we have never had any export." What he meant, and he made it very clear, was that he did not consider, as exports, sales which were made more or less in spite of their not wanting to sell abroad. It is very dangerous to consider that exports will look after themselves and the door to new markets will open of its own account. Indeed, I think the contrary is true. The sooner we try to open the door the less rusty will the hinges be, and I think that the hinges of the doors to certain markets are already very rusty. The Germans are consolidating their position, the Italians are doing the same and the French are recovering, and the longer the door stays closed the more rusty the hinges will become; and it certainly will not open of its own account.

May I suggest that the export executive, awkward as he may seem at times, should be accepted as a member of the team. He may seem funny when he comes in with a drawing scaled in millimetres, but I suggest that you ask him to translate it into inches; he can usually do it in his head. If he insists that temperatures should be given in degrees centigrade, it is quite a reasonable request. In fact, a great deal can be done by the technical side to help the export department.

**Mr. E. A. Logan:** I wish to comment upon the development of the internal domestic use of electricity as an alternative to the development of electrical exports.

I should not like it to be felt that there is any lack of ingenuity or enthusiasm in this country for the development of domestic uses of electricity. There are electricity undertakings in this country which can match any of the favourable development figures which have been quoted by a previous speaker. The ingenuity is there and the will is there, but there are other factors which are beyond the control of those responsible and which have seriously limited the development of domestic electrification.

At the conclusion of the war, plant shortages resulted in a clear necessity to restrict maximum demand. That necessity was forced upon the people who would otherwise have been only too happy to set about the task of developing the domestic uses of electricity in this country. This was done for very good reasons. All the available capacity of the generating plant was needed for manufacturing for export purposes. There was also an overall restriction on capital expenditure, which meant that capital had to be applied to other ends.

I have been interested in the figures given by the author for the scale of inflation. Until recently this factor has been overlooked in many discussions of this type. A simple example to illustrate the scale of inflation is that the old 1d. red stamp has now become the 2½d. red stamp, and it does the same service.

It seems fair to suggest that one result of the provision of labour-saving appliances in houses is that an increasing number of women will be given sufficient leisure to enable them to go out to work to produce the increasing numbers of electric refrigerators and washing machines that are required.

**Mr. J. Eccles** (*President*): I should like to make the shortest contribution of all to the discussion by asking the author, with

reference to Fig. 4, how we managed to increase our exports during the war years.

**Dr. D. A. Bell** (*communicated*): Since I was unable to understand how a decrease in the value of the pound sterling from 1952 to 1953 in the ratio of about 47 : 45 (Fig. 3) could change an export expansion of nearly 30% in value to an almost constant rate by volume (Fig. 4), I consulted recent official statistics.* The relevant data are given in Fig. A, from which it can be

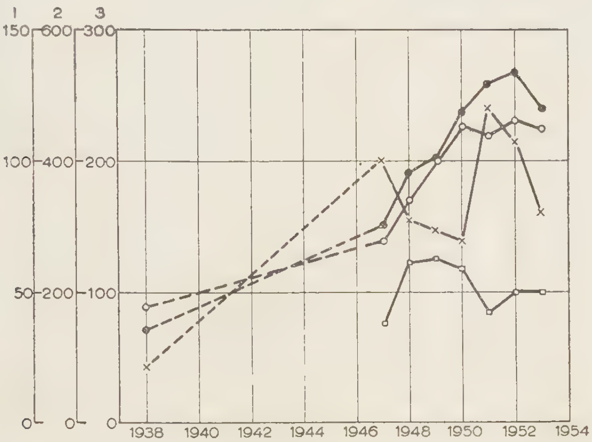


**Fig. A**

● Value of exports of electrical machinery, apparatus and appliances (see scale 1, the units are in millions of pounds sterling) at 1947 values.
× Volume of exports of domestic radio receivers, radiograms, etc. (see scale 2, the units are in thousands).
○ Volume of exports of electrical machinery (see scale 1, the units are in thousands of tons).
□ Volume of exports of cables and wires (see scale 3, the units are in thousands of tons).
The scaling of curves ×, ○ and □ is not related to their proportions in the total value (curve ●).

seen that the changing value of the pound sterling is not a very large factor in the situation. (This would have been more obvious if Fig. 3 had not been drawn with a suppressed zero.) Corrected export prices of electrical goods appear to have risen sharply since 1950.

The author philosophizes about the tendency to shorter working hours, but official statistics† show no such tendency in the post-war engineering industry, as can be seen from the following Table giving the average number of hours worked weekly in the engineering, shipbuilding and electrical-goods manufacturing industry:

| Year | 1948 | 1949 | 1950 | 1951 | 1952 | 1953 |
|---|---|---|---|---|---|---|
| Average number of hours worked weekly | 45·7 | 45·6 | 46·4 | 46·9 | 46·9 | 46·9 |

It is often said that Great Britain has lagged behind in mechanization because labour in this country has in the past been more plentiful and cheaper than in the United States. We now have a labour shortage, and the immediate problem is whether mechanization can be introduced fast enough to maintain the desired sum of both military and civil production. The problems of surplus labour and leisure have become more remote of recent years.

In suggesting that research on the efficiency of turbo-alternators is not of the highest importance, the author ignores the role of coal in the British economy. Since it is almost the sole indigenous raw material and one for which there is a ready export market, yet it is in short supply, any economy in the combustion of coal is of the utmost importance immediately as a contribution to the balance of payments and ultimately in terms of the use of coal as a raw material for the chemical industry.

In view of the acknowledged importance of exporting goods which include the minimum of imported raw materials, I suggest that we should concentrate on valves and cathode-ray tubes. At least the vacuum which occupies so large a part of their volume is innocent of any imported raw materials. Moreover, if a British firm had produced the transistor, as well as a British firm having found an economic method of recovering germanium from British sources, the contribution of the electronics industry to the dollar balance might well have exceeded the leading contribution traditionally supplied by whisky. The difficulty is that one cannot predict the next major developments, and the investment in research needed to ensure a good chance of "drawing the next winner" is uncomfortably high.

No one doubts that the only way to maintain a large population in these islands is by the export of skill; but the difficulty is to decide whether to concentrate on craft skill (cf. the Swiss watch industry) or on scientifically based industry (cf. the Swiss chemical industry). In addition to jet engines and nuclear power units, a possible line would be machine tools, including automatic devices, and electronic computers; but this line is handicapped by the limited use of such devices by British industry, and it may well be that the market in electronic computers is already lost to the United States.

**Mr. J. Solomon** (*communicated*): The author refers to the psychological factors involved in presenting the need for increased productivity in objective terms that can be generally understood. Perhaps one form of subjective approach may achieve some success in correlating the curves in Fig. 2 with additions showing the range of wages and salaries in the electrical engineering industry, over the period shown, and with regard also to the correction factors of Fig. 3. If any marked deficiencies are thus revealed, and then corrected by the industry in an appropriate manner, it is probable that one of the psychological difficulties will be overcome. Could the author supply the information suggested?

## THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

**Mr. G. L. E. Metz** (*in reply*): The discussion has covered such a wide field that it is quite impossible to deal with all the questions which have been raised. In attempting an objective reply I have therefore considered what we are seeking to discover from the discussion and how far we have got toward that objective.

To begin with, it is necessary to point out that the paper was not intended to stand alone; it is a continuation of an earlier paper read before The Institution in 1946. The first paper was written when the United Kingdom was emerging from the Second World War and was passing through a difficult period of reconstruction. It attempted to summarize some of the difficulties which lay ahead and to outline the way in which the electrical industries could help to surmount them. The general conclusions were that the electrical industries must endeavour to increase production and exports, and should help other industries to do likewise. In the discussion which followed it was generally agreed that further inquiry was necessary to ensure that the limited production resources available to the country were used to the best advantage.

The paper was criticized—I think correctly—as being little more than a collection of production, import, export and employment statistics. It enabled the size and progress of the electrical

* Central Statistical Office: "Annual Abstract of Statistics 1954, No. 91" (H.M. Stationery Office).
† *Loc. cit.*

industries to be compared with those of other industries. But it was clear from the discussion at London and Manchester that there were many important issues that could not be resolved by a mere recital of statistics. It came as a shock to many members to find that, although the electrical industries had had an almost unbroken run of prosperity since 1938, the country as a whole had, during the same period, been passing through a severe economic crisis which could not be surmounted without quite extraordinary efforts which they, in common with others, would have to make.

It was against this background that the second paper was written, with the object of recording the progress that had been made and the changes that had occurred which were likely to affect the electrical industries. First and foremost, it was necessary to record that in the spheres of technical knowledge, of production and of exports progress had, from every point of view, been quite remarkable. The electrical industries had continued to run ahead of many others, and production, exports and employment continue to increase far above the average rate for all industries taken together. On the other hand, during the same period the economy of the country as a whole has remained balanced on a knife edge and could easily have been brought tumbling down by any slackening of effort or by unfavourable external influences. This was mainly because the reserves of what might loosely be called "working capital" were sufficient to cope with adverse trading conditions for only a very limited period. But if progress in the electrical industries and the general economic climate have continued much as they were in 1946 there have been other changes which seem likely to have a profound effect on the industry and all those engaged in it. It was brought out in the discussion that, in the circumstances of full employment such as obtain at present, additional production can be achieved only by the better use of the plant, power and human effort at our disposal and by doing, by means of machines and mechanical power, operations at present done by hand. The electrical industries provide the power and the machines for doing this, and on them therefore depends to a large extent whether production in and exports from the United Kingdom rise or fall. So in a few years circumstances have elevated the electrical industries from a humble position to one of the leading parts on the stage of national affairs.

It is, however, a little disconcerting to find that, in spite of all that has been done, Britain's share of world trade has been and still is falling and that the prosperity which the electrical industries have experienced is to some extent due to favourable external influences that are passing and are unlikely to return. Although advances in technical knowledge have removed nearly all the barriers to efficient production, there still remain side by side in many industries production units that are models of efficiency and others which are reminiscent of the nineteenth century. It is not necessary to go far to find operations and processes that could be carried out more efficiently by means of electrical power and machinery, and it is not too much to say that far more is to be gained by the full application of the knowledge we already possess than from the new discoveries on which so much of our present energies are expended. Not the least of our problems is to find out why technical knowledge which has been available for many years is not fully applied in our own and in other industries.

Col. Leeson points out that the electrical industries can contribute only as much as society will allow them to do and as much as they can pay for. I feel that this is very much at the crux of the present situation and causes one to wonder whether the industry is devoting enough attention to publicizing the aids to production they have already produced and urging the application of them in other industries which they serve. In this connection it was pointed out that it is now possible to control and run factories automatically without the use of operating labour and to replace the large staffs at present used for such services as the calculation of wages and of P.A.Y.E. by electrical calculating and computing machines.

The working out of a new balance between the work to be done by hand and that to be done by machine is to a considerable extent a matter for the electrical engineer, and one has only to visualize the situation that would arise if everything were to be done by machinery and men were paid to lounge about and consume the products of the machines to realize the difficult social problems that would follow any other than a reasonably accurate balance. Probably the most important consideration brought out in the discussion was that the growing size and importance of the industry make it of more rather than less importance to have periodic reviews of the type attempted in the paper, and emphasizes the fact that electrical industries now occupy such an important position in national affairs that their future progress can be measured only in terms of their contribution to society.

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Paper No. 1797
Apr. 1955

# THE ADHESION OF ELECTRIC LOCOMOTIVES

By H. I. ANDREWS, Ph.D., M.Sc., M.I.Mech.E., Member.

*The paper was first received* 30*th October*, 1954, *and in revised form* 5*th January*, 1955. *It was published in April*, 1955, *and was read before* THE INSTITUTION 28*th April*, 1955.)


## SUMMARY

After the results of previous investigations have been considered, ie paper describes measurements of adhesion made on electric ocomotives on the recently electrified lines between Manchester, heffield and Wath. Measurements were made under controlled onditions with the aid of the mobile testing plant on one driving axle f a locomotive, the tractive effort of this axle being separately regu-ted, and on all driving axles of a locomotive in normal condition, hile the adhesion of locomotives working trains in service was bserved by the use of dynamometer cars. It is shown that there xists a relationship between adhesion and speed, and between adhesion nd water on the head of the rail, while variations in adhesion were ound to occur between different parts of the track. A subsidiary ivestigation revealed that considerable variation occurred in the alues of the locomotive axle loads during running. Various methods f temporarily improving adhesion were investigated, such as the se of sand or of certain esters. The conclusions are particularly onsidered in relation to the working of trains up the Wentworth icline; recommendations are made as to the methods of driving to e employed under difficult conditions; and a modification to the ocomotive control to increase adhesive performance is described.


## (1) INTRODUCTION

In the early days of railways concern was felt as to whether ie degree of frictional resistance existing between the driving heels and the rails was sufficient to enable a locomotive to aul a train of reasonable weight, and some pioneers, such as lenkinsop (1812), provided a definite rack-system for that urpose. It was soon established, however, that, except for steep iountain railways, natural adhesion was sufficient for ordinary urposes, although the limiting value of adhesion available has ways been regarded with some uncertainty, since it varies con-derably with the state of the rail surface and other circum-ances. Early electric locomotives were designed on the basis f comparable steam locomotives, with a "factor of adhesion," r ratio between the maximum value of the tractive effort and e total load on the driving wheels, in the neighbourhood of 25. In 1928 Lipetz recommended for design purposes factors f adhesion based on a true limit of adhesion ratio of either 0·32 0·30, depending on circumstances, as given in Table 1. The gures given for a "locomotive with uniform torque" may be nployed for electric locomotives provided that the true values f maximum tractive effort are used: otherwise the variation of active effort due to notching of the control must be taken into ccount, and this, for a typical d.c. locomotive, would represent a alue of $\lambda$ of about 1·11. In modern designs of electric loco-otive the horse-power applied to each driving axle is steadily nding to increase, and adhesion is rapidly becoming the niting factor in design, so that, in view of the wide variation adhesion experienced in service, the need for further investi-tion of this subject is becoming imperative.

During the intervening years, many attempts have been made measure the limiting values of adhesion on all types of loco-

Dr. Andrews is with British Railways.

**Table 1**

RECOMMENDED FACTORS OF ADHESION
Lipetz, 1928

| Type of locomotive | $\lambda$ | Factor of adhesion | |
|---|---|---|---|
| | | True coefficient of adhesion: 0·32 | True coefficient of adhesion: 0·30 |
| 2-cylinder steam locomotive: cut-off 70% or more | 1·23 | 0·250 | 0·234 |
| 2-cylinder steam locomotive: cut-off 50–60% | 1·16 | 0·259 | 0·243 |
| 4-cylinder steam locomotive: cranks at 90° | 1·11 | 0·278 | 0·260 |
| 3-cylinder steam locomotive: cranks at 120° | 1·07 | 0·289 | 0·271 |
| Locomotive with uniform torque | 1·00 | 0·315 | 0·295 |

$\lambda = \frac{\text{maximum value}}{\text{average value}}$ of driving torque.

motive, but the results have generally been confused by the fact that friction varies considerably with the nature of the rail surface and other factors, so that not only did the observations vary between very wide limits, but also the results obtained were often contradictory. Such measurements were difficult to make with the conventional steam locomotive owing to the cyclic variation in the torque applied to its driving wheels, so the more reliable results have been obtained by the use of electric motors or by frictional braking, either of which means provides a steady tractive effort. Many investigations have been carried out on these lines, and the whole of this work has been summarized by Koffman,[1] who analyses the results on, as far as possible, a common basis. The friction of a wheel actually slipping on a rail is also considered, since it is well known that the coefficient of friction is reduced once slipping has commenced.

One of the first aspects to be considered in the study of adhesion is the relationship between the limiting value of adhesion and the speed of the train. This is of particular importance, not only because it offers a clue to the nature of the action of a wheel upon a rail, but also because a falling coefficient of adhesion with increase of speed would represent a major limitation to the high-speed performance of locomotives. Many investi-gators have reported a greater or lesser degree of falling off of adhesion with increase of speed under otherwise (apparently) similar conditions. Thus, in 1927 Wichert[2] measuring the motor current at which slipping occurred in a 1–$D_0$–1 locomotive of the German State Railways with an electrically-recording dynamometer car, as shown in Fig. 1(*a*), found that there was a considerable fall in the value of limiting adhesion on both dry and wet rails, as seen in Fig. 2. Results of a quite different form were shortly afterwards obtained by Müller[3] in tests on three types of a.c. electric locomotives on the St. Gothard and Loetsch-berg lines in Switzerland. Each locomotive in turn was made to

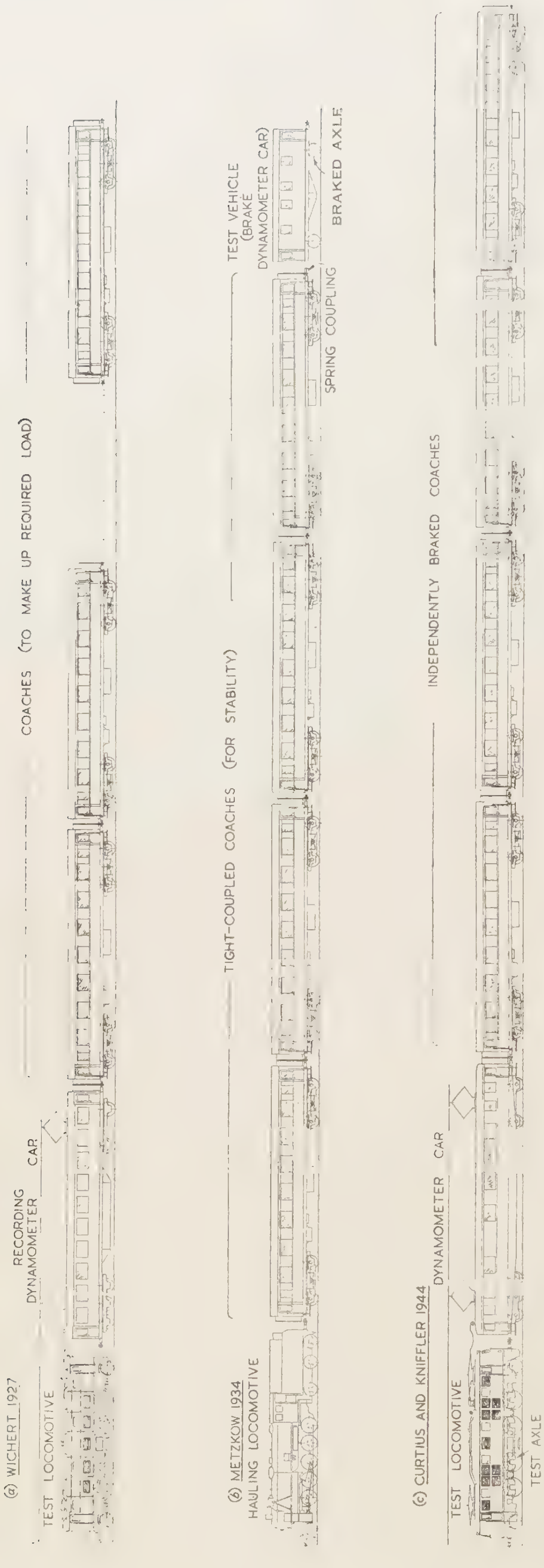



**Fig. 1.**—Previous measurements of adhesion—composition of test trains.

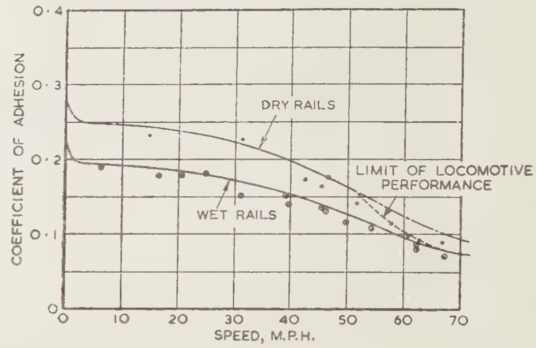



**Fig. 2.**—Measurements of Wichert, 1927—adhesion/speed relationship.

haul a train of appropriate weight up a gradient of 1 in 36–37 upon which constant conditions of running in the neighbourhood of the limiting coefficient of adhesion could be obtained, and the current in the motors was recorded by means of recording ammeters. Typical values of the coefficient of adhesion measured with and without slipping on both wet and dry rails are shown in Fig. 3, in which it is seen that the limiting adhesion falls

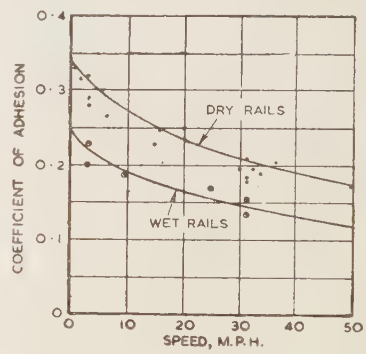



**Fig. 3.**—Measurements of Müller, 1928—adhesion/speed relationship.

rapidly with increase of speed immediately on starting. There does not appear to be sufficient difference between the types of locomotive or the methods of testing of Wichert and Müller to account for the considerable divergence of their results.

These conclusions were again contradicted by the results of another investigation carried out by Metzkow[4] in 1934. The tests, which were undertaken at the Grunewald locomotive testing station of the German State Railways were made on the line between Grunewald and Güsten, with a train as shown in Fig. 1(*b*). A steady source of tractive effort was obtained from a steam locomotive closely coupled to a number of coaches, which served to haul a long-wheelbase four-wheel dynamometer car to which they were loosely coupled. In addition to the normal braking, either axle of the dynamometer car could be independently braked by means of an air-operated disc brake. When a suitable stretch of line was reached, braking was gradually applied to one axle until slipping of the wheels occurred, during which time a continuous record was taken of the pull at the dynamometer drawgear, the air pressure applied to the brake, and the rate of revolution of the wheels. Measurements were made in this way of the limiting coefficient of adhesion with three different values of axle load. A typical set of results of these tests is shown in Fig. 4, in which it is seen that, up to the limit of the observations at 60m.p.h., the limiting values of adhesion must be regarded as substantially independent of speed.

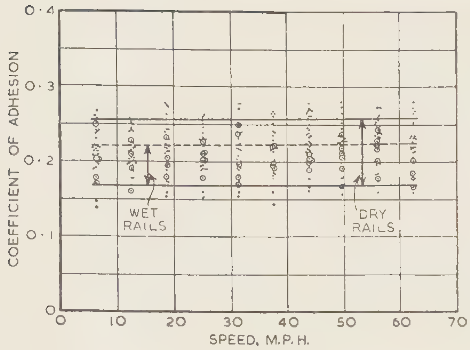



Fig. 4.—Measurements of Metzkow, 1934—adhesion/speed relationship.

...... Measurements on dry rails.
○○○ Measurements on wet rails.

A further analysis of the records obtained in these tests was later made by Pflanz.[5] It appeared that after slipping had commenced with a slowly rolling wheel there was an intermediate stage in which a high value of adhesion was maintained, even in face of appreciable slip, though this rapidly disappeared as the measure of slip increased. From these results Pflanz was able to relate the falling value of adhesion to the increased rate of slipping at various train speeds.

In 1944 a further series of adhesion tests were carried out by Curtius and Kniffler[6] at the electrical testing station of the German State Railways at Munich. Tests were made on a $1\text{–}D_0\text{–}1$ type a.c. electric locomotive coupled to a dynamometer car and four coaches to which braking could be applied independently, as shown in Fig. 1(*c*). The locomotive was worked normally until an opportunity for testing occurred, when three of the four main motors were cut out and the train continued with only one motor working. The load could then be gradually increased by applying the brakes to the following coaches until slipping of the test driving-wheels began. The results obtained, seen in Fig. 5, have a form similar to those of Wichert, but

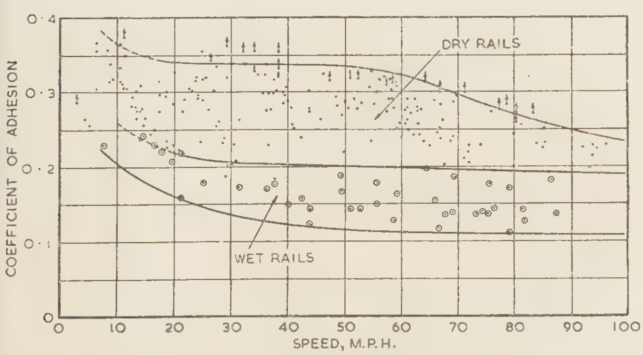



Fig. 5.—Measurements of Curtius and Kniffler, 1944—adhesion/speed relationship.

much higher values. In analysing these results an attempt was made to relate the values of adhesion to the prevailing conditions, and it was particularly noted that higher values of adhesion were often obtained earlier in the day, even though the weather conditions remained unchanged, presumably owing to the roughening effect of dampness or dew during the night being gradually worn away by the traffic during the day.

It has often been claimed that coupling rods improve the adhesion of locomotives, though individual drives are usually preferred for d.c. locomotives where the speed/torque characteristics of the series motor ensure that the load is equalized between the driving axles. But in the case of a.c. locomotives, or where it is desired to employ one large motor in preference to a number of smaller ones, there are many advantages in distributing the load between the driving axles by means of rods. Bager and Ottoson[7] therefore carried out comparative tests on two a.c. locomotives, one of the Swedish State Railways of the 1–C–1 type with rod drive, and one of the Göteborg–Borås Railway of the $B_0\text{–}B_0$ type with individual axle drives. The results, some of which are represented in Fig. 6, show that over

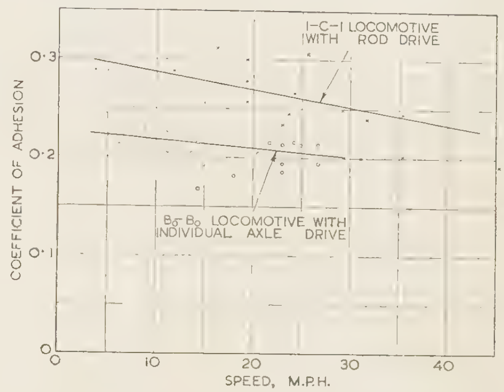



Fig. 6.—Comparison of adhesion of locomotives with rod-drive and individual axle drives.

Taken on dry rail.

The figures plotted are calculated on a basis of static adhesion weight. If corrected for torque reaction the figures for the $B_0\text{–}B_0$ locomotive would be 14·4% higher.

30% greater adhesion could be obtained with the rod-drive locomotive, with even higher values at low speeds. Of this improvement only 14·4% was attributable to the weight transfer effect in the bogie locomotive, and the remainder must therefore be due either to redistribution of load between the coupled and uncoupled axles in the rod-drive locomotive, or to improvement in the adhesion itself.

Values of adhesion are also employed in locomotive design for other purposes besides the estimation of maximum tractive effort. Thus, for example, the fact that the adhesion at the tread of the driving wheels has a definite limit is often regarded by designers of gears, flexible drives, and similar mechanisms coming between the motor and the wheels, as a means of overload relief. Royer[8] makes the interesting claim that if, as is generally believed, the value of adhesion falls with increase in the rate of slipping, a locomotive will be less liable to slip at any speed if it is arranged that the rate of fall of tractive effort of the motor with increase of rotational speed exceeds the rate of fall of adhesion with increase of slipping speed.

## (2) INVESTIGATION ON THE MANCHESTER–SHEFFIELD–WATH ELECTRIFICATION

In view of the contradictory nature of these results it was doubted whether any real improvement in the employment of adhesion could be achieved until the whole problem of rail friction was better understood. Accordingly, in 1939, plans were made by the former London, Midland and Scottish Railway for an investigation into this subject, which, however, had to be postponed. The problem was again considered by the Railway Executive in 1952, in connection with the Manchester–Sheffield–Wath electrification, on which some difficulties with adhesion were being experienced. In addition to the main line between Sheffield and Manchester, this system includes the

Worsborough branch from Barnsley Junction, near Penistone, to Wath Marshalling Yard. This branch, most of which is used by good trains only, serves mainly to convey trains of Yorkshire coal, which are made up at Wath, up to Penistone, whence they continue on the main line through the Woodhead Tunnel into Lancashire. As this line crosses the main Pennine range severe gradients are encountered, and on the Worsborough branch, a profile of which is shown in Fig. 7, there is the Wentworth Bank,

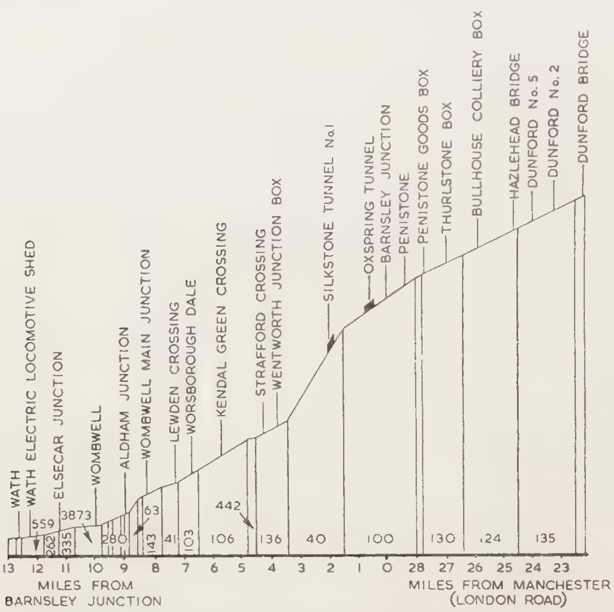



Fig. 7.—Gradient diagram of Worsborough Branch: Manchester–Sheffield–Wath electrification.

Including Penistone–Dunford Bridge section of main line.

which has a gradient of 1 in 40 for about two miles. Moreover, this line is subject to severe mining subsidence, so there is always the possibility that short lengths of track may be at an even greater inclination. In 1951 the whole of this branch had been opened for electrically hauled traffic, together with the portion of the main line between Barnsley Junction and Dunford Bridge, so that the trains which were marshalled at Wath could be hauled electrically to the line summit at Dunford Bridge, whence they were taken over by steam locomotives for the descending portion of the journey.

The electrification is carried out at a nominal voltage of 1 500 volts d.c. with overhead contact-line and rail return. The locomotives employed on these services are of the $B_0 + B_0$ type, as shown in Fig. 8, with four axle-hung nose-suspended

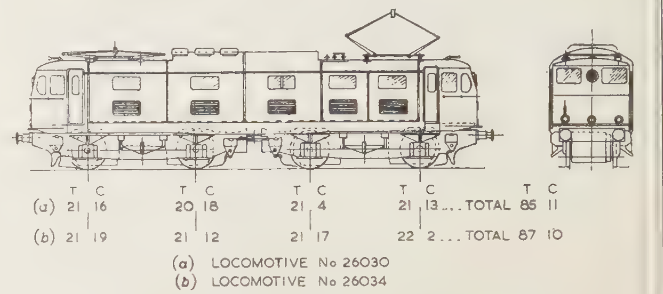



Fig. 8.—Outline of $B_0 + B_0$ locomotive.

Weight of bogie . . . . . . . . 19 tons 0cwt.
Unsprung weight of axle, etc. . . . . 5 tons 8cwt 2qr.

motors. Their circuit arrangement is shown schematically in Fig. 9, and the characteristics of the motors, which are permanently connected in pairs in series, are given in Fig. 10. They are equipped with regenerative braking, so that the trains descending an incline can help to haul the ascending trains in the other direction.

When electrical working began on this line, trains were usually made up at Wath Yard to a nominal maximum load of 850 tons including the guard's van, and were hauled to Dunford Bridge by one train locomotive with the assistance of one uncoupled banking locomotive at the rear. While, in general, no difficulties were experienced, occasional failures due to locomotives slipping on the Wentworth Bank in exceptional conditions were reported during the winter of 1951–52. For this and other reasons it was decided temporarily to reduce the maximum load from 850 to 750 tons. At the same time it was decided to put in hand an exploratory investigation into the whole question of locomotive adhesion with the threefold object, first, of obtaining a better understanding of frictional adhesion at the rims of locomotive driving wheels, secondly, of measuring the adhesion available on this particular type of locomotive, and thirdly, of studying the performance of these locomotives under actual service conditions. It was hoped that the infor-

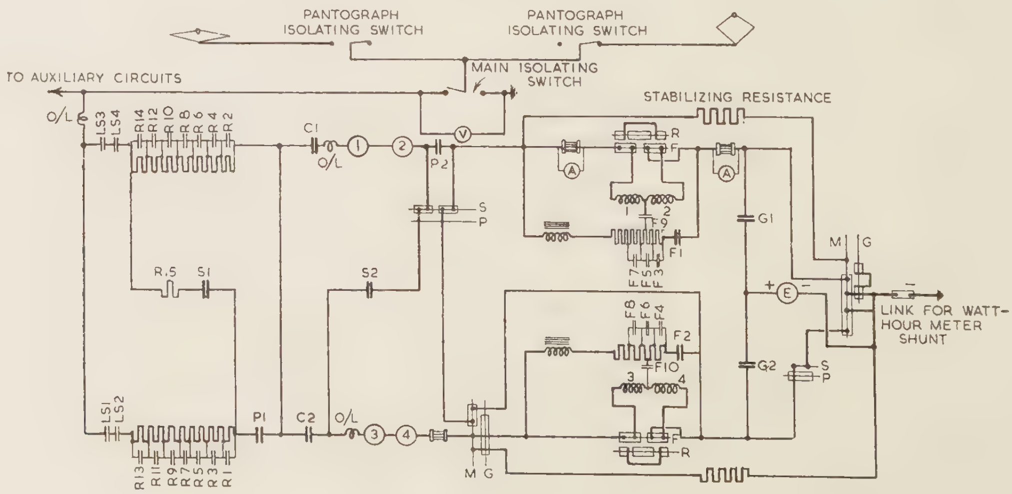



Fig. 9.—Schematic of circuit of $B_0 + B_0$ locomotive.

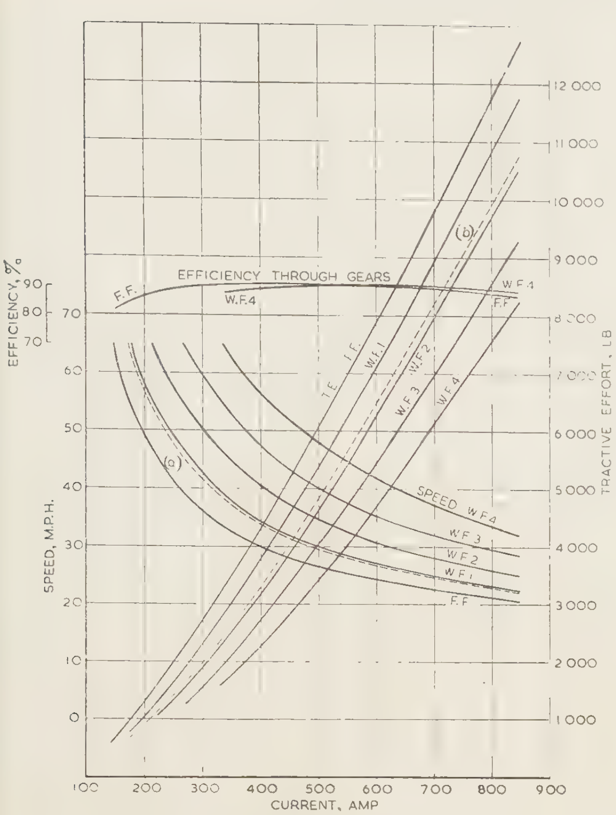



**Fig. 10.**—Characteristics of motor of $B_0 + B_0$ locomotive.

Performance at 700 volts.

50in diameter wheel. 17/70 gear ratio. Speed (r.p.m.) = 27·7 × m.p.h.
Broken curves show performance with weight-transfer compensating notch.
(a) Shows combined speed at 1 400 volts of two motors in series.
(b) Shows tractive effort of motor on axle which has reduced adhesion.

nation obtained in this or subsequent investigations might be f assistance in the design of further types of electric rolling tock to work at high values of speed or tractive effort—by ndicating the reasons for the occasional failures that had ccurred, and in suggesting means by which the adhesional apacity of these or similar locomotives could be increased.

### (3) DESCRIPTION OF TESTS

In order to segregate the effects of the various factors involved, was decided that measurements of limiting values of adhesion hould first be made under the following conditions:

(a) Under constant conditions of speed and tractive effort on one pair of wheels of a locomotive in which arrangement would be made so that the tractive effort applied to these wheels could be finely varied at will.

(b) Under constant conditions of speed and tractive effort on all four pairs of wheels of another locomotive in normal condition.

(c) On all wheels of locomotives hauling maximum loads under normal service conditions, and in particular when ascending the Wentworth Bank.

Two locomotives were used in these tests, Nos. 26030 and 26034, whose general particulars were as given above. Locomotive No. 26030 was employed in its normal condition throughout; while Locomotive No. 26034 was sometimes employed in normal condition, and sometimes its circuit was rearranged as shown schematically in Fig. 11, so that only the No. 2 axle was motored and its tractive effort could be controlled and finely adjusted. In order that the maximum tractive effort of the one motor could be maintained at the higher speeds, the other motor of the pair was short-circuited and the current passed through the whole of the starting resistance, so that as the speed increased the voltage applied to the motor could be increased in steps up to double its normal value. Finer regulation of the motor current was obtained, first by the introduction into the earthed end of the circuit of a "vernier" set of cast-iron resistors of lower value with intermediate tappings and contactors, and secondly, by using the motor-generator normally employed for regenerative braking as a field-controlled voltage booster. The additional resistance contactors were controlled by switches temporarily installed in one driver's compartment, while the regulating field of the motor-generator was controlled by the regenerative braking handle in the usual way. By these means the tractive effort applied to the No. 2 axle could be very gradually increased well beyond the normal limit so that the exact conditions at the moment at which wheel-slip began could be observed.

In order that they could be tested under constant conditions and their working studied, the locomotives were first attached to the mobile testing plant, a special train which has been constructed for the purpose of testing locomotives in actual running. This apparatus, which is shown in Fig. 12, has been fully described elsewhere,[9] and includes one, two or three electric-braking vehicles with a combined dynamometer and control vehicle. The electric braking absorbs the power of the locomotive and is automatically controlled by an electronic regulator so that the speed of the train is maintained constant within 0·15m.p.h. of any desired value, so that all effects due to acceleration are substantially eliminated. In addition to its usual functions, the dynamometer and control vehicle served

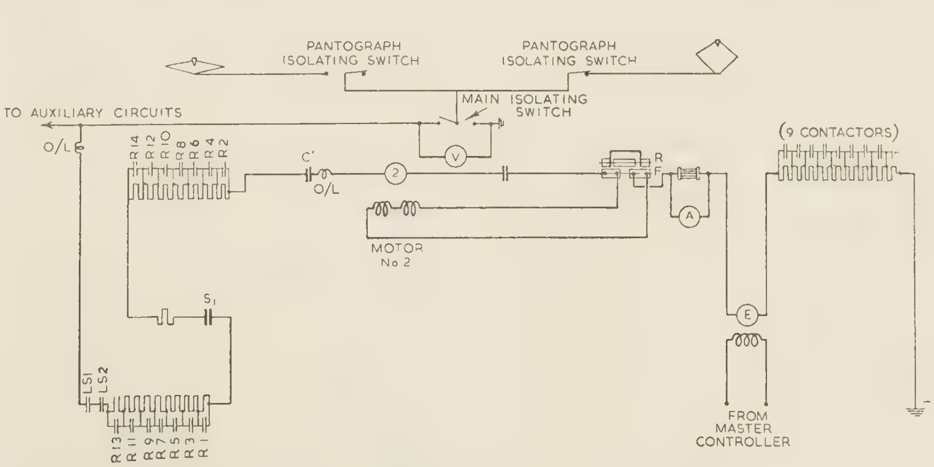



**Fig. 11.**—Schematic of temporary connections of Locomotive No. 26034 using only one motor.

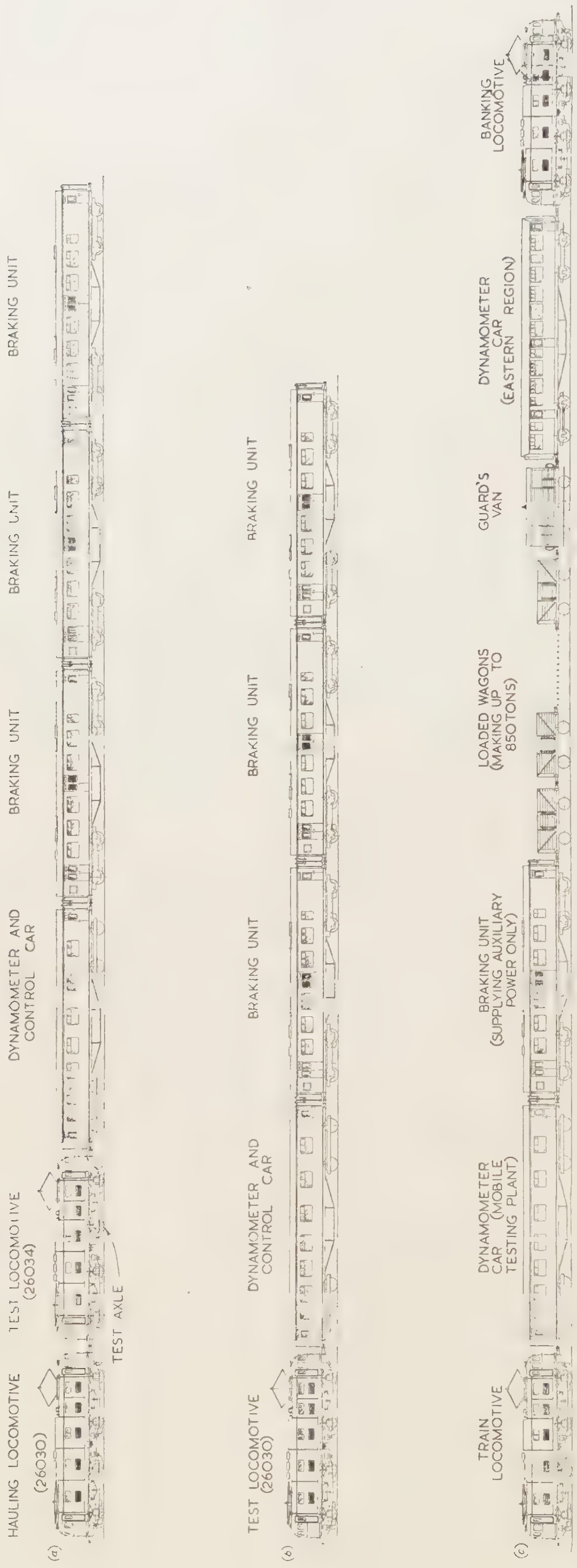



**Fig. 12.**—Measurements of adhesion on Manchester–Sheffield–Wath electrification.
Composition of test trains.

both to provide instruments from its equipment normally carrie and to carry other instruments required in the tests.

In the first series of tests, corresponding to (*a*) above, it w desired to measure the limiting coefficient of adhesion existi between the rims of one pair of driving wheels and the ra under various conditions. For this purpose a train was ma shalled as shown in Fig. 12(*a*), Locomotive No. 26034, in whic the tractive effort applied to the No. 2 axle could be separate controlled, being attached to the mobile testing plant, a Locmotive No. 26030 added at the head to provide the necessa haulage. The mobile testing plant is provided with a telepho communication system, and this was temporarily extended the driving cabs of the two locomotives so that the entire te could be directed from the central control compartment on t dynamometer car. The train was first hauled by the leadi locomotive until a suitable opportunity for testing occurre and load was applied to the braking units so that some specifie value of speed was obtained, when the automatic control w introduced and the speed was held constant throughout t period of test. Current was now applied to the No. 2 motor the test locomotive up to a value a little below that at whic slipping was expected to occur, but there was no change in t speed of the train, since the additional tractive effort was aut matically compensated by an increase in the electric braki owing to the action of the automatic control. The tractive effo applied to the test axle of Locomotive No. 26034 was then ve gradually increased by adjustment of the vernier resistance o of the voltage booster until slipping occurred, when the mot current was immediately reduced to allow the driving wheels t recover. During this time continuous records were obtained o the current in the test motor, the drawbar pull, the speed, t location on the track, and the occurrence of slip, from whic observations the true values of limiting adhesion could be ca culated for successive points on the line. At the end of each te period the load on the mobile-testing-plant braking units w removed, and control of the train returned to the driver of t leading locomotive.

During these tests the current of the test-axle motor wa recorded by means of a recording ammeter whose reading were co-ordinated with the corresponding records of draw bar pull, speed, location, etc., automatically produced at th dynamometer recording table. The latter was of the Amsle type with hydraulic dynamometer gear and spherically int grating mechanisms. Slipping was indicated by means of tw permanent-magnet generators, one driven from the test ax and the other from the freely running No. 1 axle at the othe end of the same bogie. These tachometer generators, whic were mounted on the respective axleboxes and were drive through duplicate sets of bevel gearing, each gave a signa voltage of some 200–400 volts, so that, by connecting them i opposition across a voltmeter having a range of only 10 volt as shown in Fig. 13, a very sensitive indication of any differenc

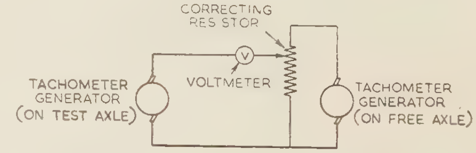


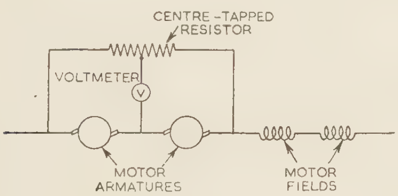

**Fig. 13.**—Method of indicating slip on test axle of Locomotiv No. 26034.

in their respective speeds was obtained. As tractive effort wa applied to axle No. 2 only, while axle No. 1 was allowed to ru freely, any degree of slipping of the test driving wheels produce

proportionate movement of the pointer of the indicating oltmeter.

The first tests were made in this manner at a constant speed f 5m.p.h. in dry weather within the limits of Wath Exchange idings, observations being made when travelling in both direcions at various points along the track. Following these, a eries of journeys was made between Wath and Dunford Bridge 1 both directions under different weather conditions, obserations being made at different speeds at a large number of oints along the line. Testing was limited to speeds below bout 30m.p.h., since, even with the doubled voltage at the notor terminals, it was usually impossible to obtain sufficient orque above that speed. Since the performance of the motors vas related to the adhesion of the driving wheels, it was necessary or the current in the test motor to be increased beyond its normal hort-period rating, and care had to be taken that neither the notor nor its resistors became unduly heated. While for most bservations the tractive effort was increased so gradually that ne results could be regarded as representative of constantactive-effort conditions, some observations were made with ifferent rates of increase of tractive effort, while a few obserations were made with the tractive effort applied in the reverse irection to that of running, so that the difference between the miting coefficients of adhesion in the forward and reverse irections could be ascertained.

In the next series of tests, corresponding to (*b*) above, only ocomotive No. 26030 was employed, this being in normal ondition, but coupled to the mobile testing plant, as shown in ig. 12(*b*). With this train further journeys were undertaken 1 each direction between Wath and Dunford Bridge under ifferent weather conditions, and observations were made of ipping of the driving wheels which was produced by notching p under otherwise constant conditions. The train was driven 1 the normal manner until an opportunity for testing occurred, hen it was brought under automatic control at some value of onstant speed as before. The driver was then instructed to otch up slowly until slipping of one or other of the pairs of riving wheels occurred. Slipping of any of the driving wheels as indicated in this case by two voltmeters with centre-zero ales, connected as shown in Fig. 14, one instrument serving




g. 14.—Method of indicating slip on either axle of one bogie of Locomotive No. 26030.

r each pair of axles, the slipping axle being indicated by the rection of movement of the instrument pointer. The current which slipping occurred was recorded by two recording nmeters, one in each of the motor circuits. Records were also ade of the drawbar pull, speed, location, etc., on the dynamoeter recording table as before. By correlating the results of ese tests with those of the preceding series, the actual conditions working of the locomotive could be studied.

For the third series of tests Locomotive No. 26034 was turned to its normal condition and the two locomotives were nployed, as train engine and banker respectively, to haul the aximum load of 850 tons from Wath to Dunford, including e ascents of the Wentworth Bank. On each return journey 0 tons of (mostly) empty wagons were brought down the hill with the use of regenerative braking, the two locomotives being together at the head of the train. During these tests the locomotives were operated in the normal manner throughout, but the train, shown in Fig. 12(*c*), included two dynamometer cars, one at each end, so that the performance of the two locomotives could be recorded during the journey. The first dynamometer car was London Midland Region Car No. 3 of the mobile testing plant, which in this case was working independently, except that one braking unit was attached to provide auxiliary power. The second dynamometer car was Eastern Region Car No. 999500. By comparison of the actual performance of the locomotives with that estimated from the results of the two previous series of tests, the special factors affecting the working of the locomotives in these difficult circumstances could be studied. In most of these tests notching up was limited to the series connection, but in a few tests the locomotives were put into the parallel connection when ascending the Wentworth Bank. Other tests were made with the load reduced to 750 tons, while four journeys were made during the severely cold nights of the 24th and 25th November, 1952.

Finally, one test was made for the purpose of determining the performance of the locomotives. For this test one locomotive, No. 26030 in normal condition, was attached to the mobile testing plant, as in Fig. 12(*b*), and worked on the line at various values of constant speed between 10 and 50m.p.h. At each value of speed the locomotive was run for a short distance in the full series and the full parallel positions, in the various weakfield notches in both the series and parallel connections, and with the weight transfer switch open and closed. During this test continuous records were obtained of the drawbar pull, the two motor currents, and the line voltage, and these were related to the location of the train on the line so that the drawbar characteristics of the locomotive could be determined. It had also been intended to determine the running resistance of the locomotive separately by towing it at various constant speeds and measuring the necessary pull with the dynamometer car, but for this form of test a line of fairly constant gradient is required, and it was found that the local irregularities of gradient on the Worsborough Branch, which are due to mining subsidence, rendered it unsuitable for this purpose.

### (4) MEASUREMENTS OF ADHESION

It was first necessary to calculate the drawbar characteristics of the locomotive from the results of the performance tests, and these are given in Fig. 15. Since these values are dependent upon the line voltage they were suitably corrected and values for both 1 500 volts and 1 400 volts are given. Since it was impossible for the values of the locomotive resistance to be measured direct they were deduced by comparison of the drawbar figures with the corresponding figures obtained through gears on the manufacturer's test-bed. The resistance values so determined were somewhat spread since it was difficult to measure the drawbar characteristics exactly owing to the local variations in gradient and the fact that the running resistance amounted only to some 2–3% of the forces to be measured. Nevertheless, by taking average values of a large number of observations, reasonably consistent values could be obtained, and are shown in Fig. 16 as pounds per ton of the complete weight of the locomotive.

From the records obtained during the tests on Locomotive No. 26034 the coefficient of adhesion existing immediately prior to each slip could be determined. The current in the test motor gave the nominal tractive effort produced at the rims of the test driving wheels by comparison with the motor characteristics obtained through gears. From this was deducted the running

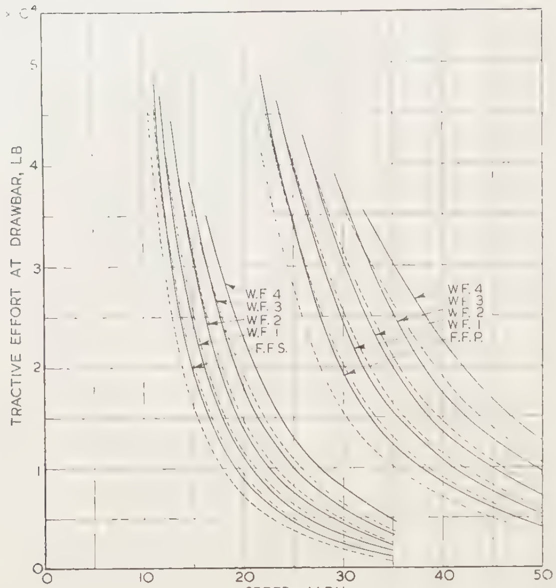



**Fig. 15.**—Tractive effort at drawbar of $B_0 + B_0$ locomotive.

——— 1 500 volts.
– – – – 1 400 volts.
Measured and corrected for voltage.

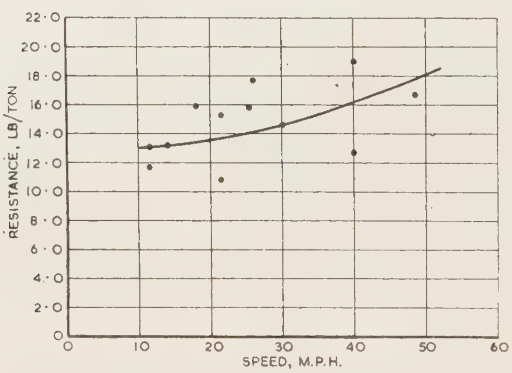



**Fig. 16.**—Running resistance of $B_0 + B_0$ locomotive.

resistance associated with the test axle, which, as the locomotive had four motor-driven axles, was taken as one-quarter of the total running resistance of the locomotive. The load at the tread of the test driving wheels was taken as the measured value of the axle load corrected for the change of load produced by the torque reaction, calculated from the motor torque and the dimensions of the bogie as described in the Appendix. From these corrected values of load and tractive effort the value of the coefficient of adhesion at the moment of slipping was obtained.

While care was taken to ensure that all measurements were taken under closely controlled conditions, it was at once evident from the results that there was considerable spread in the observations. This spread was doubtless the result of varying factors such as speed, dryness of rail, etc., but since the number and nature of such factors was unknown it was felt to be impossible, with the information available, to undertake a complete statistical examination of the results. It was therefore necessary to follow the usual exploratory technique of separating the variables as far as possible and plotting against each variable in turn. Thus the most difficult variable, the dryness of the rail, was first eliminated by separating those observations in which the rail surface could be described as either "completely dry" or "completely wet." These observations still contained a considerable measure of spread, so they were first each plotted against the most obvious variable, speed, with the results shown in Figs. 17 and 18. As the observations were grouped at parti-

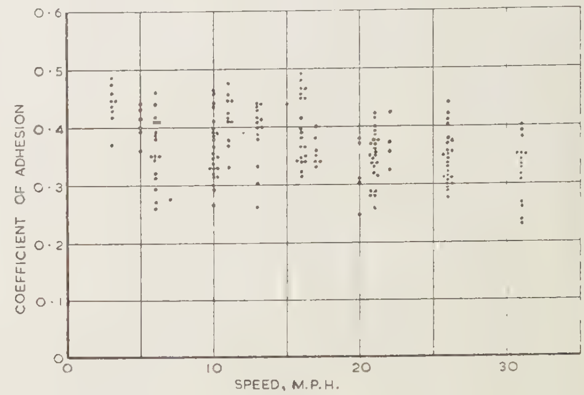



**Fig. 17.**—Corrected values of adhesion on dry rail measured on one axle of Locomotive No. 26034 at constant speed.

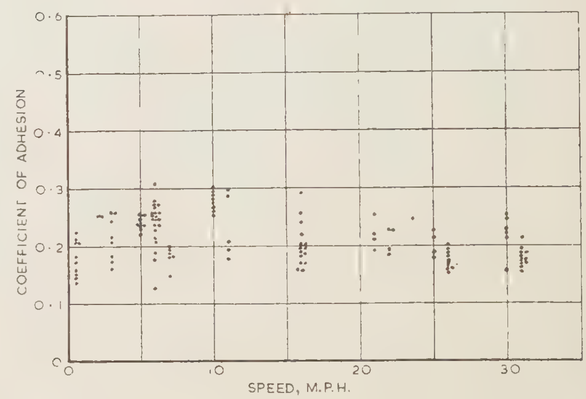



**Fig. 18.**—Corrected values of adhesion on wet rail measured on one axle of Locomotive No. 26034 at constant speed.

cular values of speed, the average value for each group was obtained and replotted for both dry and wet rails as shown in Fig. 19. It is clear that there is a reduction of the limiting adhesion with increase of speed, and that, over the range

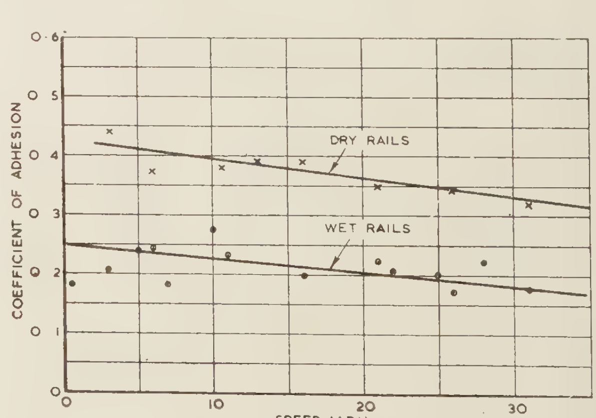
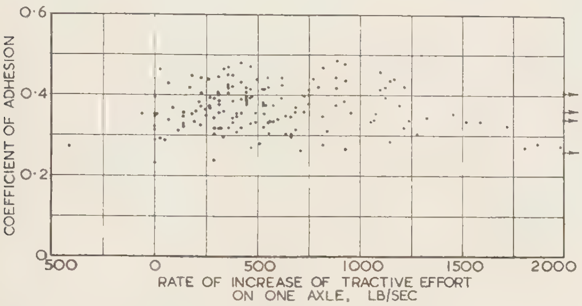


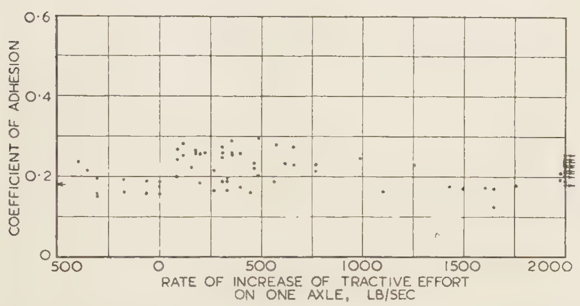

**Fig. 19.**—Average corrected values of adhesion measured on one axle of Locomotive No. 26034 at constant speed.

ıeasured, the amount of this reduction is roughly proportional ) the speed.

Another potentially relevant factor was the rate of increase of ıe tractive effort which existed at the rims of the driving wheels nmediately prior to slipping. These values were determined om the records taken of the motor current. The values of dhesion taken on a dry rail are plotted against the rate of ıange of tractive effort in Fig. 20, and on a wet rail in Fig. 21.




ig. 20.—Corrected values of adhesion on dry rail, measured on one axle of Locomotive No. 26034 at constant speed, related to the rate of increase of tractive effort.




g. 21.—Corrected values of adhesion on wet rail, measured on one axle of Locomotive No. 26034 at constant speed, related to the rate of increase of tractive effort.

rom these figures it seems reasonably clear that the rate of ıange of tractive effort has little or no bearing on the adhesion ılues obtained.

The next factor to be considered was the dryness of the rail ırface, but here the difficulty arose that it was not possible to ɔtain an exact measure of this quantity during the tests. However, qualitative observations were available from which it was lt that an indication of the amount of water on the head of e rail might be obtained. Accordingly a length of rail in pical condition was installed in the laboratory, and the observed nditions reproduced with measured quantities of water. While was not possible to gauge the amount of water corresponding each observation with any accuracy, it was found that these ıounts could be reproduced with certainty to the order of ten. ıus heavy rain could produce as much as 0·1 lb of water per ıare foot on the head of the rail, while a typical greasy rail d about 0·001 lb of water per square foot. Very small quanies of water gave quite clear visual indications; for example, e film of moisture obtained with mist or dew probably reprented only about 0·00001 lb of water per square foot. Since is difficult to ensure that any object is completely free from ɔisture, it was decided that the term "completely dry" should taken as representing not more than 0·000001 lb/ft$^2$. The servations could now be replotted against the estimated amount of water on the head of the rail, which, for convenience, was represented on a logarithmic basis, with the results shown in Fig. 22. While the exact nature of the relationship indicated by these results is not certain, it is clear that the adhesion values obtained on a dry rail are gradually decreased as the amount of

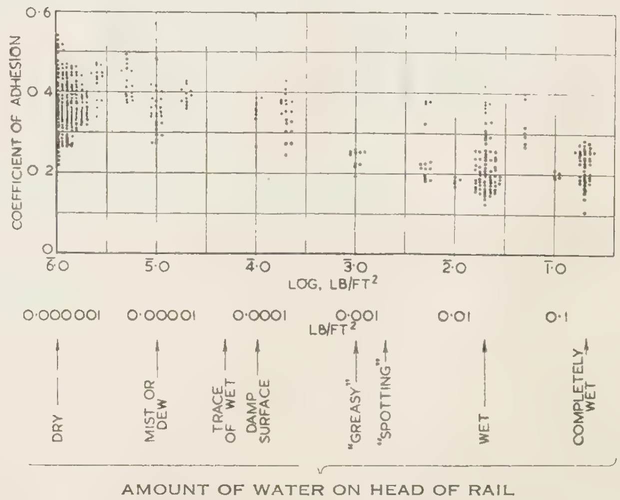



**Fig. 22.**—Corrected values of adhesion, measured on one axle of Locomotive No. 26034 at constant speed, related to the estimated amount of water on the head of the rail.

Dry rail taken as $1 \times 10^{-6}$ lb/ft$^2$ of water on rail head, or less.

water on the rail increases until a value of about 0·001 lb/ft$^2$ is reached, after which it appears that any increase in water has no appreciable effect on the adhesion.

Thus the adhesion values measured were found to be a function of the speed and of the weight of water on the head of the rail, but since the spread of the corrected results still considerably exceeded the probable experimental error, it seemed that there must be at least one other major factor affecting the results. As the nature of such factor was unknown the observations were further examined to ascertain whether they could be related to any other circumstance. It was found that there was clearly some relationship between the value of adhesion in any particular conditions with the location at which the observations were taken along the line. Thus, for example, some observations taken at approximately constant intervals during a number of runs in each direction over the length of Wath Exchange sidings at a constant speed of about 5 m.p.h., plotted in Fig. 23, show a definite pattern in relation to the distance along the track. For some reason the adhesion had a maximum value near the middle of the siding and fell off sharply towards the two ends. The results of certain series of tests, taken within a limited range of speed, were therefore plotted in relation to the location at which they were taken along the line. Probably the most interesting are those shown in Fig. 24, in which two sets of observations taken in two successive runs in the same direction at the same speeds over one particular length of track on a very wet day are recorded. Since the weather could be regarded as the same for the two runs it is natural that there should be agreement between the observations, but the degree to which the two sets of observations combine in following a particular pattern is striking. Similarly the observations shown in Fig. 25, which were taken in both directions on two parallel tracks on different days and under greatly differing weather conditions, also show a definite tendency towards a form of pattern over the same length of line. So far no entirely satisfactory explanation has been found to account for this "rail factor," which must in some way be associated with

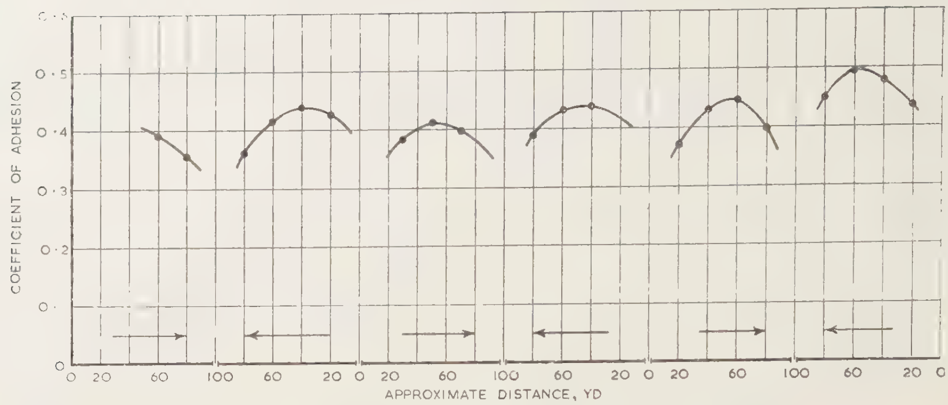



Fig. 23.—Measurements of adhesion made in dry weather in Wath Exchange sidings.

⟶ Measurements in "down" direction.
⟵ Measurements in "up" direction.
Taken at constant speed 5m.p.h.

the permanent way, and possibly with the nature of the rail surface.

Since this rail factor could not be related to any measurable quantity, it was impossible to ascertain whether it accounted for the whole or most of the remaining spread of the observations, although Fig. 24 suggests that, under suitable weather conditions, observations could be repeated with reasonable accuracy. For the same reason it was impossible to carry out any complete statistical examination of the results. At this stage, therefore, it can only be concluded that the coefficient of adhesion obtainable at any point on the rail is dependent upon the speed of the train, upon the amount of moisture on the head of the rail, and upon some factor connected with the rail itself. No appreciable difference could be determined in the adhesion whether the tractive effort was applied in the positive or the braking direction.

In general, the measurements of adhesion obtained on Locomotive No. 26030, which was tested in normal operating condition, were in agreement with the more exact results obtained from the single-driven-axle of Locomotive No. 26034. Observations at speeds greater than about 22m.p.h. were difficult to obtain, since, each pair of motors being permanently connected in series, only one-half of the line voltage could be applied to any one motor. The observations taken on dry rail are shown in Fig. 26. At the lower speeds these seem to be a little lower than those measured on Locomotive No. 26034, shown in Fig. 17, and, while making allowance for the effect of the voltage limitation, there appears to be a definite tendency for the adhesion to fall more rapidly with increase in speed than was the ca with Locomotive No. 26034. The difference in loading betwee the two axles of each bogie, caused by the weight transfer du to torque reaction, was compensated by closing the weigh

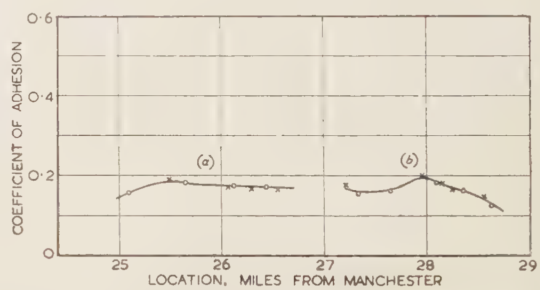



Fig. 24.—Selected measurements of adhesion showing variations adhesion with location under the same weather conditions.

⊙ Measurements made during morning of 6th November, 1952.
× Measurements made during afternoon of 6th November, 1952.
All measurements made while running in the "up" direction.
Rails very wet. Speeds were constant and the same in each case.
(a) Speed 30 m.p.h. (b) Speed 25 m.p.h.

transfer switch. However, it was noted that, when slipping d occur, it was invariably at the leading axles of the bogies, ind cating that the weight transfer correction was, to some exten incomplete.

From the results of the service trials it appeared that in d

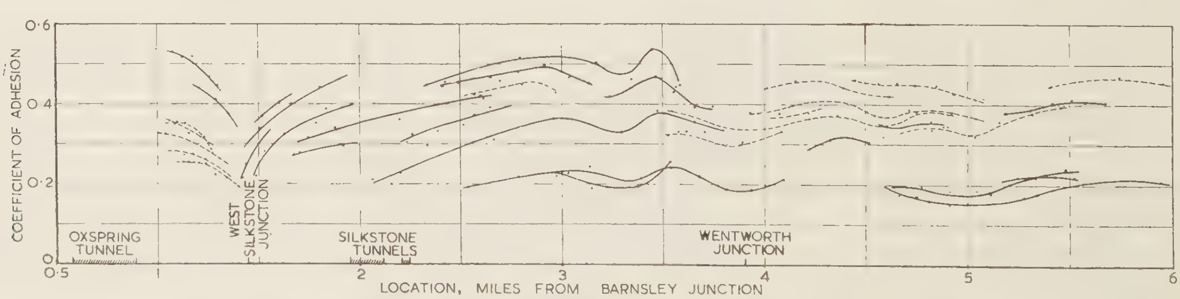



Fig. 25.—Selected measurements of adhesion showing variation of adhesion with location under differing weather conditions.

——— Down line.
– – – – Up line.
Taken at constant values of speed 5–20m.p.h.

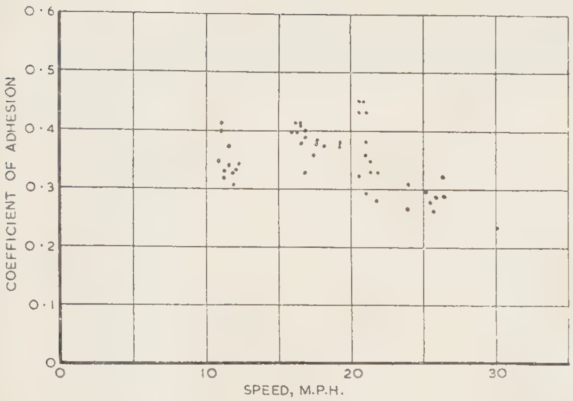



Fig. 26.—Corrected values of adhesion on dry rail measured at slipping of any axle of Locomotive No. 26030 (in normal condition) at constant speed.

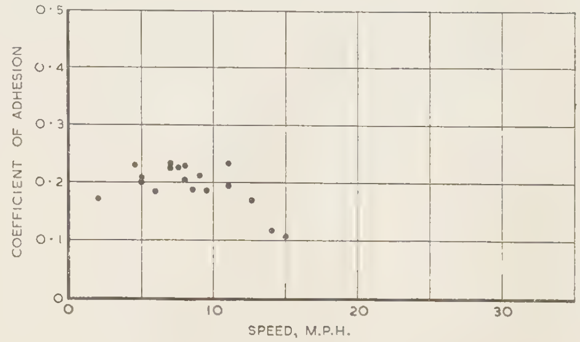



Fig. 27.—Corrected minimum values of adhesion measured on Locomotive No. 26030 (in normal condition) in service.

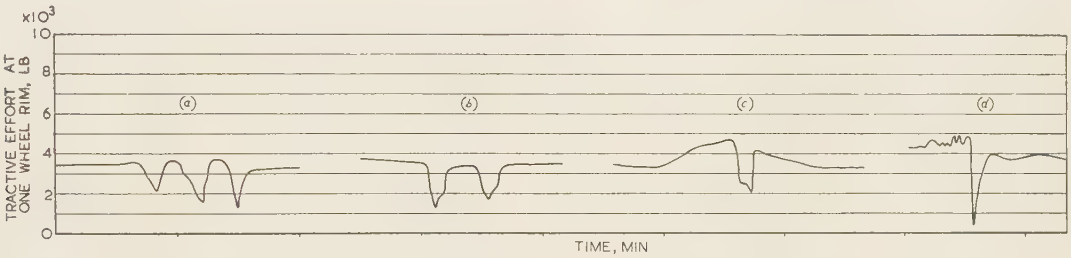



Fig. 28.—Incipient slips observed on Locomotive No. 26030 (in normal condition) in service.

(a) 14th November, 1952. Constant speed: 15m.p.h. Rail very wet.
(b) 3rd December, 1952. Constant speed: 30m.p.h. Rail damp.
(c) 18th November, 1952. Normal working: 16m.p.h. Rail damp.
(d) 25th November, 1952. Normal working: 14m.p.h. Rail damp during night.

weather no difficulty was experienced in taking the full 850 tons up Wentworth Bank with the two locomotives in normal condition, the one acting as train locomotive and the other at the rear. In wet weather slipping did occasionally occur, and complete failure resulted on two occasions during the day working. Subsequent examination of the records revealed that on these occasions there was lack of co-ordination between the two drivers at the opposite ends of the train, and the slipping often occurred at higher values of tractive effort than were really needed for hauling the train. No appreciable slipping occurred with loads of 750 tons, or with the trains descending the incline under regenerative braking. The conditions under which slipping occurred were so varied that no particular relationship could be deduced from their values. During the runs up the bank in parallel very little slipping occurred, which may be partly attributed to the fact that, at the speeds obtained on the bank with parallel running, there was sufficient time for any small slip to be corrected owing to the higher momentum of the train. During the runs at night, one complete failure occurred owing to slipping, and lack of co-ordination between the drivers again appeared to have been the principal cause. The minimum values of adhesion at which slipping occurred throughout these service trials have been selected, and are shown in Fig. 27, from which it is seen that a value of adhesion of 0·17 without sand may generally be relied upon at low speeds under normal working conditions. The records also show that on certain occasions there were a number of incipient slips, such as those shown in Fig. 28, where slipping actually began at a value of adhesion of about 0·16, but these subsequently disappeared, and apparently the drivers were not aware of their occurrence.

## (5) METHODS OF IMPROVING ADHESION

In railway operation it is usually envisaged that the natural adhesion of a locomotive should be sufficient for its working in all ordinary circumstances, but that sanding of the rails may be employed in bad weather or circumstances when the natural value of adhesion is reduced. This practice is followed with the Manchester–Sheffield–Wath locomotives, as with other electric locomotives, with the difference that the sand is necessarily applied by an air jet instead of the steam jet usual with a steam locomotive. Many authorities[10,11,12] claim that sanding can produce coefficients of adhesion of from 0·33 to 0·50, or some 50–100% more than is usually relied upon with natural adhesion. Metzkow[4] recorded values of adhesion on dry sanded rail varying between 0·25 and 0·48 in the course of a single series of tests. During the service trials sand was applied on a number of occasions when slipping had occurred or was imminent, but it appeared from the records that often very little improvement was obtained, certainly far less than would be expected from the results of these previous investigators.

A further series of tests with Locomotive No. 26034 and the mobile testing plant, marshalled with the other locomotive as shown in Fig. 12(*a*), was therefore put in hand to measure the effect of sanding direct. Care was of course taken to ensure that the sanding apparatus employed was working correctly. Measurements were made of the adhesion both with and without sanding under dry and wet conditions at various speeds. To eliminate the effects of changes in dryness and in the rail factor, observations were taken alternatively with and without sand, and the difference was expressed as the percentage improvement obtained with the use of sand. The results so obtained, for both

dry and wet conditions, are shown in Fig. 29. Three features of these results are particularly noticeable: the variation between the results of different observations, the reduction of the improvement due to sanding with increase of speed, and the number of

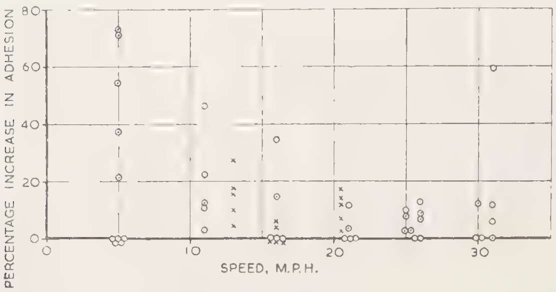



**Fig. 29.**—Tests with sand: proportional increase in coefficient of adhesion with use of sand under wet and dry rail conditions measured on one axle of Locomotive No. 26034 at constant speed.

○ ○ ○ Measurements on wet rail.
× × × Measurements on dry rail.

occasions when the application of sand produced no noticeable effect whatever. Since sanding did, on occasion, increase the adhesion by as much as 60–70%, there must be some reason why the full effect was realized on so few occasions, and this point is being further investigated.

As an alternative to sanding, consideration was given to the use of other substances which could temporarily increase the friction at the rims of the driving wheels. Following the work of Schnurmann,[13,14] it was decided to try very dilute solutions of a suitable ester in either water or oil, and a further series of tests was carried out within the limits of Wath Exchange sidings in which the limiting coefficient of friction was measured at the driving wheels of Locomotive No. 26034, as before, while small amounts of these solutions were deposited on the rails immediately ahead of the wheels. As the object of such measures would usually be to improve adhesion on wet rails, and to ensure a constant rail condition, the surfaces of the rails were sprayed with water immediately before each test. It was found that the best results were obtained with a thin even layer of ester solution on the rail, and at first this was difficult to obtain reliably, but after a number of trials a temporary arrangement using a felt pad was arrived at, which served for the immediate purpose of the tests. Three different solutions were tried: a saturated solution (approximately 0·5%) of ethyl stearate in water, a 1% solution of ethyl caprylate in water, and a 1% solution of ethyl oleate in a light spindle oil.

These tests were intended only to be exploratory, and limited results were achieved until an even film of solution was obtained over the head of the rail. The felt pad adopted was of course only a temporary expedient which will doubtless be replaced by some more permanent apparatus, such as a fine spray. The average results from each series of tests with ethyl stearate and ethyl capryllate are given in Table 2, and it is seen that, even in the limited tests undertaken, the use of these solutions could markedly improve the adhesion of a wet rail, and the project must therefore be regarded as one of promise. Comparable results obtained with ethyl stearate and ethyl capryllate appeared roughly to correspond, but the use of ethyl stearate is to be preferred owing to its practical and commercial advantages. It was noticed that, not only did these solutions tend to increase the value of static adhesion, but also the value of sliding adhesion was increased to an even greater extent, so that a higher value of tractive effort could be maintained after slipping had commenced. This effect was particularly marked in the tests with the solution of ethyl oleate in oil, a typical record of which is shown

**Table 2**

Coefficients of Adhesion obtained on Wet Rail with the use of Ester Solutions

| Conditions of test | Average coefficient of adhesion | Percentage improvement |
|---|---|---|
| Wet rail (as prepared for each test) .. | 0·245 | — |
| *With application of ½% ethyl stearate solution:* | | |
| Steady jet on one rail only .. .. | 0·226 | — |
| Steady jet on both rails.. .. .. | 0·239 | — |
| Steady drops .. .. .. .. | 0·222 | — |
| Slow drops .. .. .. .. | 0·261 | 6·5 |
| Very slow drops .. .. .. | 0·259 | 5·7 |
| Steady jet 12 in ahead .. .. .. | 0·247 | 0·8 |
| Steady jet 3 in ahead .. .. .. | 0·247 | 0·8 |
| *With application of 1% ethyl capryllate solution* | | |
| Steady drops 12 in ahead .. .. | 0·257 | 4·9 |
| Steady drops distributed over rail head | 0·318 | 29·8 |
| Steady jet on felt distributor .. .. | 0·311 | 27·0 |
| Felt distributor with soaked pad only | 0·311 | 27·0 |
| Steady jet on felt distributor; 10 m.p.h. | 0·295 | 20·4 |
| Steady jet on felt distributor; 2 m.p.h. | 0·324 | 32·3 |
| *Comparative observations:* | | |
| Dry rail .. .. .. .. .. | 0·383 | 56·3 |
| Steady jet of water on dry rail.. .. | 0·273 | 11·4 |
| Copious flow of water on dry rail .. | 0·227 | — |

Average figures measured at a constant speed of 5 m.p.h. on thoroughly wetted rail, unless otherwise stated.

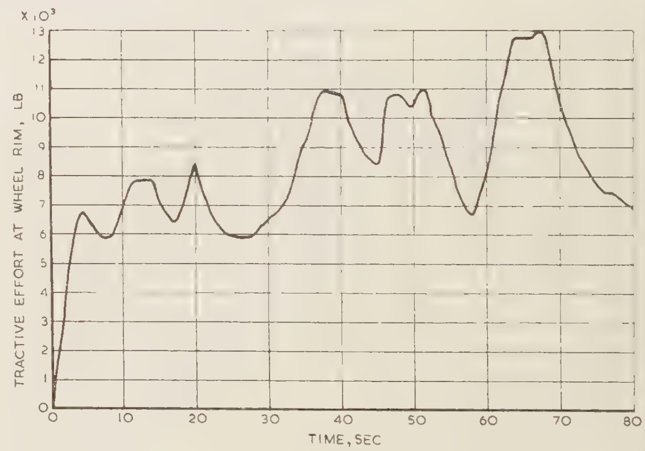



**Fig. 30.**—Typical record of tractive effort at rim of one pair of wheels of Locomotive No. 26034 at constant speed of approximately 5 m.p.h., showing adhesion on wet rails with a 1% solution of ethyl oleate in oil.

Nominal axle load, 21 tons 9 cwt.
Steady slipping of the wheels was occurring over most of this period.

in Fig. 30, when the nominal point of slipping seemed to disappear into conditions of sliding adhesion, and a considerable value of tractive effort was maintained with continuously slipping wheels. While otherwise the results obtained with ethyl oleate were less favourable than those of the other solutions, this function might be of considerable value in train operation since slipping would be less serious, and, since there would be more time to correct a slip, failures on a steep gradient would be more easily avoided. For the moment, however, the use of ethy

tearate appears to offer the best possibilities, and, since this is eally only water slightly tainted with ester, it represents an conomic alternative to sand which must be purchased in bulk ind dried, whereas the ester solution is easily handled and seems nore reliable in action.

### (6) INVESTIGATION OF AXLE LOADS

One of the most interesting features of the results described ibove was the fact that the adhesion obtainable with Locomotive No. 26030 was a little less, and appeared to decrease more rapidly vith increase of speed, than would be indicated by the results btained under more closely controlled conditions on Locomotive No. 26034. Consideration was given to this point, and a umber of possible explanations were followed up without success. Change in the actual coefficient of adhesion seemed unlikely, ind since it had been found that rate of change of tractive effort iad no appreciable effect, it appeared that there must be some hange either in the tractive effort or in the axle load. A variation of a transient nature was further suggested by the occasional inexplained slips at apparently low factors of adhesion, shown n Fig. 28, which had been observed in both locomotives when vorking in service in normal condition. Sufficiently large hanges in tractive effort could hardly occur without some ndication being observed in the readings of the motor ammeters, o it was decided to investigate the axle loads in actual running. The form of variation suggested by the observations was of a beriod of at least several seconds, and the slip indicators had hown that small slips were usually of only brief duration, so t was felt that high-frequency vibrations or forces associated vith vertical accelerations of the wheel-and-axle assembly could, for the moment, be disregarded. Since the torque reaction of he motor was known from the records of the motor current, ind the weight of the wheel-and-axle assembly with the unsprung veight of the motor was constant, the true load at the wheel read could be determined by measuring the loads in the spring iangers.

The method employed in measuring these loads was an lectric one which had been developed for weighing on moving rains, and which has already been described in a previous paper.[15] The active element comprises essentially a coil of fine nsulated wire wound tightly around a metal bar, the load in vhich is indicated by change in electrical resistance of the coil. A complete electronic equipment for carrying out weighing in a emote position is installed in the mobile testing plant for veighing the coal on the grate of a steam locomotive when unning. Elements of the form described in Reference 15 are isually employed in compression, but experience has shown hat the properties of the materials used in their manufacture ire such that they can also be employed in tension within easonable limits of loading. A number of special spring hangers uitable for use on these locomotives were therefore made up as ension-type weighing elements with a single coil, shown in Fig. 31A. These were installed in place of the spring hangers arrying the load at each end of the axle whose load was to be veighed, as seen in Fig. 32. The tension type of element does iot lend itself to the inclusion of a compensating coil, but since hese elements were for outdoor use in contact with the locomotive frame, so that any changes in temperature would be gradual, the compensating coils were wound on special bolts, ilso shown in Fig. 31B, which were inserted into the frame in positions near the active elements, Fig. 32. The four hanger lements with their compensating coils were connected together n a single circuit (see Reference 15) so that their outputs could be combined and a single indication of the total load carried by he axle obtained. Weighing hangers of this type were installed in all four axles of Locomotive No. 26030 and on the test axle

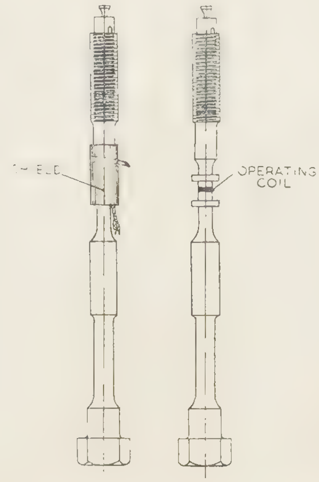



Fig. 31A.—Spring-hanger weighing elements.

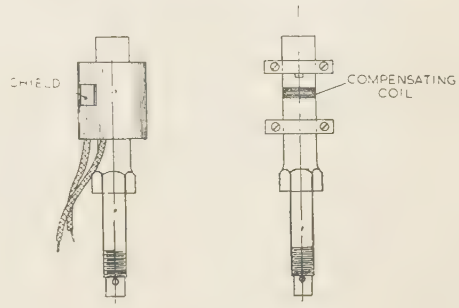



Fig. 31B.—Compensating bolts.

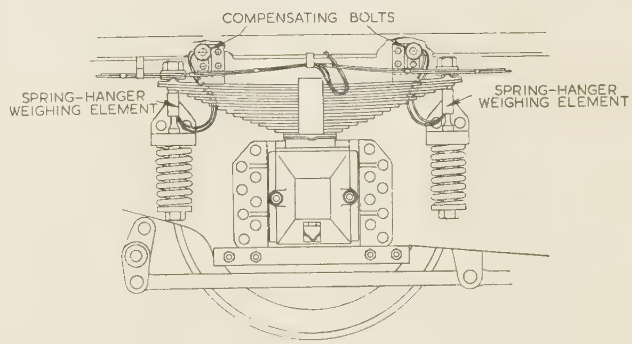
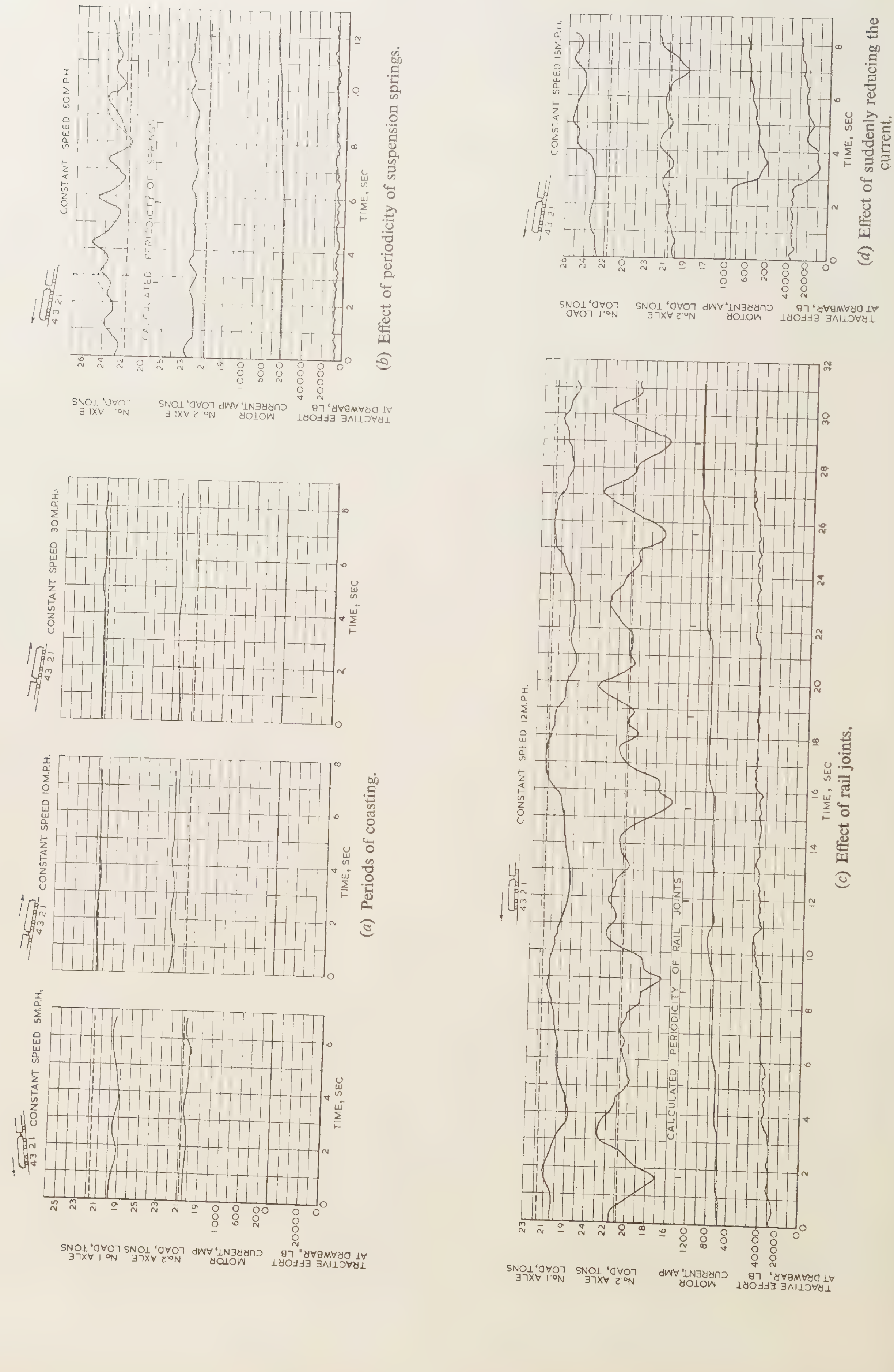



Fig. 32.—Electrical weighing arrangement for measuring loads on axleboxes.

of Locomotive No. 26034. These elements were first calibrated in the laboratory in a testing machine, and before each series of tests their readings were checked at zero load by blocking the appropriate axleboxes in their hornblocks and releasing the spring-hanger nuts. The difference between the weights indicated by the spring hangers in the loaded and unloaded conditions, plus the known value of the unsprung weight, represented the static load supported by the axle.

Observations were first made of the loads coming on the various axles of Locomotive No. 26030 in turn when running at different values of constant speed attached to the mobile testing plant, as shown in Fig. 12(*b*). It was at once apparent

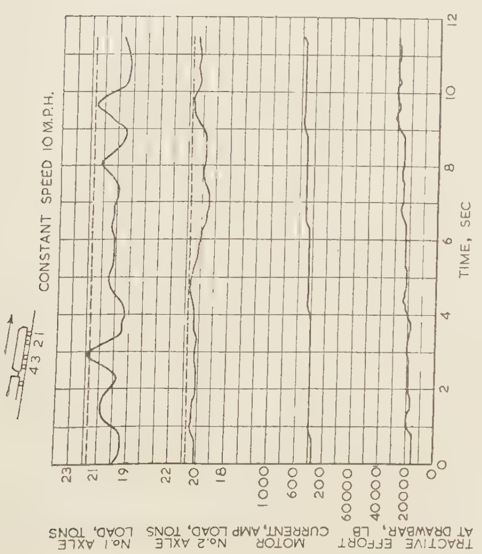


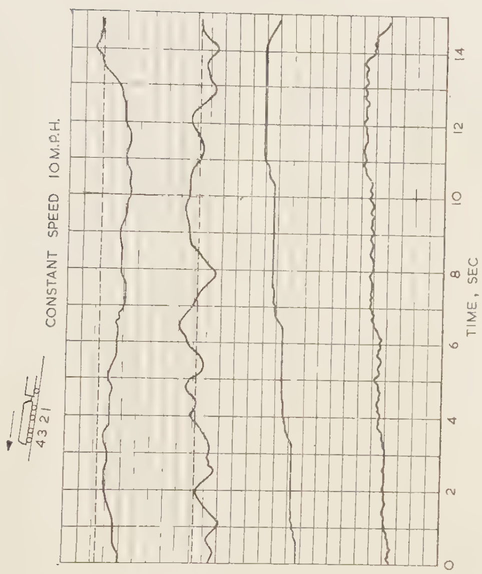

(*a*) Periods of coasting.

(*b*) Effect of periodicity of suspension springs.

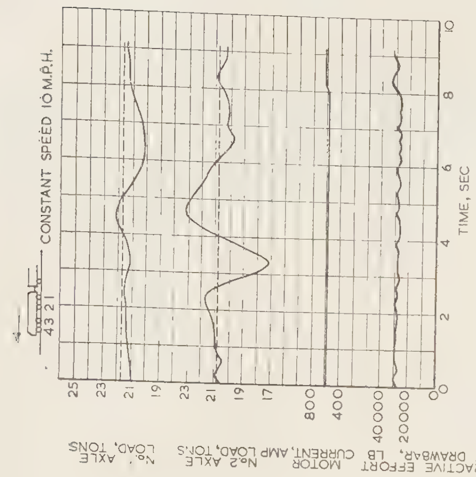
(*c*) Effect of rail joints.

(*d*) Effect of suddenly reducing the current.

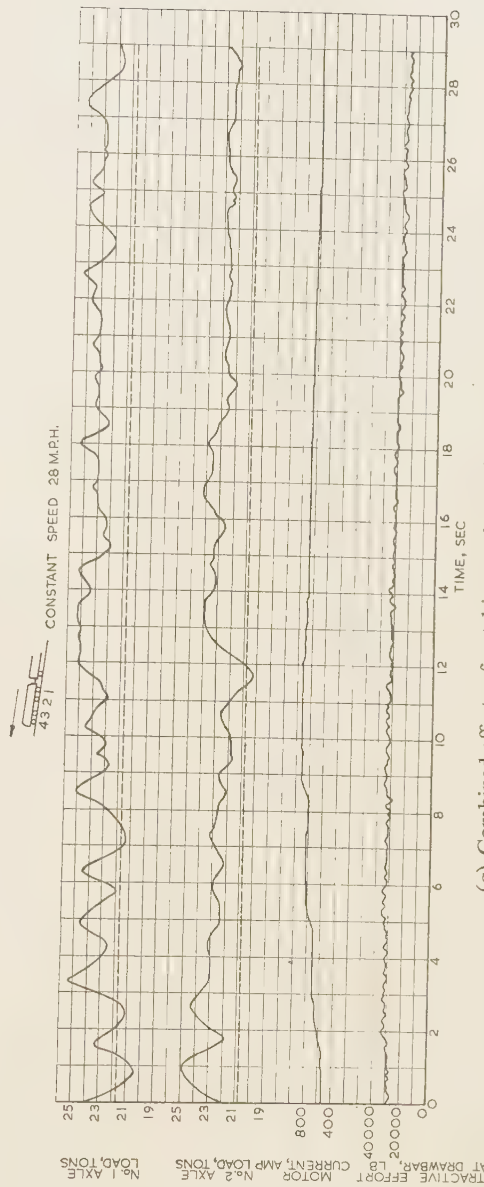



(*e*) Effect of notching up.




(*f*) Effect of a single irregularity in the track.




(*g*) Combined effects of notching, spring periodicity and rail joints.

**Fig. 33.**—Examples of transient changes of axle load recorded on Locomotive No. 26030 (in normal condition).

that there were large changes in axle load taking place whose existence had hitherto been unsuspected. Similar measurements were then made on the test axle of Locomotive No. 26034 hauled by the other locomotive as in Fig. 12(*a*). In these circumstances variations of axle load were observed corresponding to those in Locomotive No. 26030, but of less amplitude. The variations in both locomotives increased with speed and respectively caused sufficient reduction in axle loading to explain the difference in the adhesion/speed characteristics obtained on the two locomotives. Moreover, the nature of the variations in axle load occurring in Locomotive No. 26030 in normal condition would explain the occasional slips which occurred in service of the form shown in Fig. 28. These transient variations in axle load did not occur when the locomotive was coasting, so they must be in some way associated with the action of the motor, a fact which would explain the difference between the two sets of observations, since in each bogie of Locomotive No. 26030 two motors were employed, and in the active bogie of Locomotive No. 26034 only one motor was operative.

To study the behaviour of a complete bogie, two sets of electronic indicating equipment were employed, which were arranged to indicate simultaneously the loads on the two axles of one bogie of Locomotive No. 26030, and a number of further tests were carried out with this equipment at various speeds. Since it was difficult to record these indications directly, the instruments indicating the two values of load were grouped with instruments showing speed, motor current and drawbar tractive effort, and the whole group was filmed during suitable periods of the tests. These film records were subsequently measured, and certain portions are reproduced in Fig. 33. Records taken while the locomotive was coasting, shown in Fig. 33(*a*), reveal only small variations in the axle loads, such as would be expected. The variations were found to increase with increase of tractive effort, and also with speed, although there was apparently a critical value of speed at about 30m.p.h. Detailed examination of the records also showed the effect of the periodicity of the side bearing-springs, illustrated in Fig. 33(*b*), and of the rail joints, as seen in Fig. 33(*c*). Oscillations tended also to be produced by notching up, as shown in Fig. 33(*e*), or by switching off, as seen in Fig. 33(*d*). The reason for the critical condition which occurred at about 30m.p.h. is probably the coincidence of the periodicity of the bogie suspension with the passage of rail joints, which, for 60ft rails, occurs at 27m.p.h., and the particularly severe oscillations shown in Fig. 33(*g*) occurred at a time when the notching steps happened to agree roughly with the periodicity of the rail joints. Fig. 33(*g*) also shows how these oscillations tended to decrease once notching up had been completed and the current had become steady. The sole exception to these conditions was the occurrence of an occasional single impulse on the axle when running under steady conditions, such as that shown in Fig. 33(*f*), which is presumably associated with some defect in the track. It therefore appears that the bogie suspension system is liable to oscillation when the motors are working, and that such oscillation may be set up by notching, or by rail joints or other points of weakness in the track, the worst oscillations occurring when sets of disturbances happen to act together. It is quite possible that oscillations of this nature are the explanation of the differences in the results which have been reported by previous investigators; thus transient changes of axle load may easily have occurred in the locomotives used by Wichert, Müller, and Curtius and Kniffler, while they would have been unlikely in the long-wheelbase four-wheel vehicle of Metzkow. Considering the above facts, and the ratio of the rates of decrease of adhesion with speed measured on the two locomotives, it seems reasonable to suppose that the true value of adhesion is substantially independent of speed, but appears to decrease with increase of speed owing to the transie reductions in the values of the axle loads.

### (7) METHOD OF DRIVING WITH LIMITATION OF CURREN

At the conclusion of the service tests the records obtained b the two dynamometer cars were examined to ascertain why t various failures occurred. As previously stated, it was usual found that on these occasions there was lack of co-ordinatio between the drivers of the two locomotives, and when slippi occurred on one locomotive the other tended to take the fu load, thus itself beginning to slip as the first locomotive wa being brought back to work. It is natural for the drivers d.c. locomotives with a heavy train to notch up to the norm working current as rapidly as possible so as to relieve the loa on the starting resistors, but this practice tends to result i higher values of current being taken than are strictly necessar with correspondingly high values of tractive effort, so that i as with a heavy train, the period of acceleration is extende slipping sooner or later results.

These considerations suggest that if, instead of notching u as rapidly as possible, the drivers were instructed to notch u only to the minimum workable value of current, much slippin would be avoided and the load would be more evenly share between the two locomotives. The lower value of acceleratio would of course require the accelerating current to be sustaine by the resistors for a longer period, but since that current woul be lower, and the heating is proportional to the square of th current, the thermal load on the resistors need not be undul increased. The records of one of the service trials made on dry day (Fig. 34) showed that the maximum train load of 850 to could be hauled up the Wentworth Bank with the exertion of maximum value of total tractive effort, applied to the train prope of 56 000 lb, which corresponded to a current of about 675 amp i each locomotive. It was therefore decided that further tes should be undertaken to try out this alternative method o driving, and to ascertain the minimum value of maximum curre at which it would be possible to work.

A subsidiary series of tests was therefore carried out on th line between Wombwell Main Junction and Barnsley Junctio with the same two locomotives in normal condition haulin trains of 850 tons up the Wentworth Bank. During each journe the train was deliberately stopped at two points on the ban which were believed to represent positions of especial difficult and the train was restarted, the controls of both locomotive being operated in such a manner that some particular value o current was not exceeded. Tests were carried out with current limited to different maximum values, and the limiting value o maximum current with which the train could be started wa found to be 680 amp in each locomotive. Assuming a limitin coefficient of adhesion of 0·17, and taking the average value o tractive effort due to notching as 92%, an average value of actua tractive effort at the rim of the wheels of 30 304 lb is obtaine which corresponds to a current of 640 amp, from which it wa estimated that the maximum load which could be hauled up th bank under all conditions was about 800 tons.

From the results of these tests it appears that, by driving th locomotives in such a manner that the appropriate value o current is not exceeded, slipping is less liable to occur, bette co-operation between the two drivers is assured, and the sam weight of train can be hauled up or restarted on the maximur gradient with reasonable certainty in all weather condition In service it is unusual for the train to be stopped on the wors gradient, and the fact that during the tests two starts were mad in succession without undue heating of the resistors implie that there was adequate thermal capacity in the resistors for the to be employed in this way.

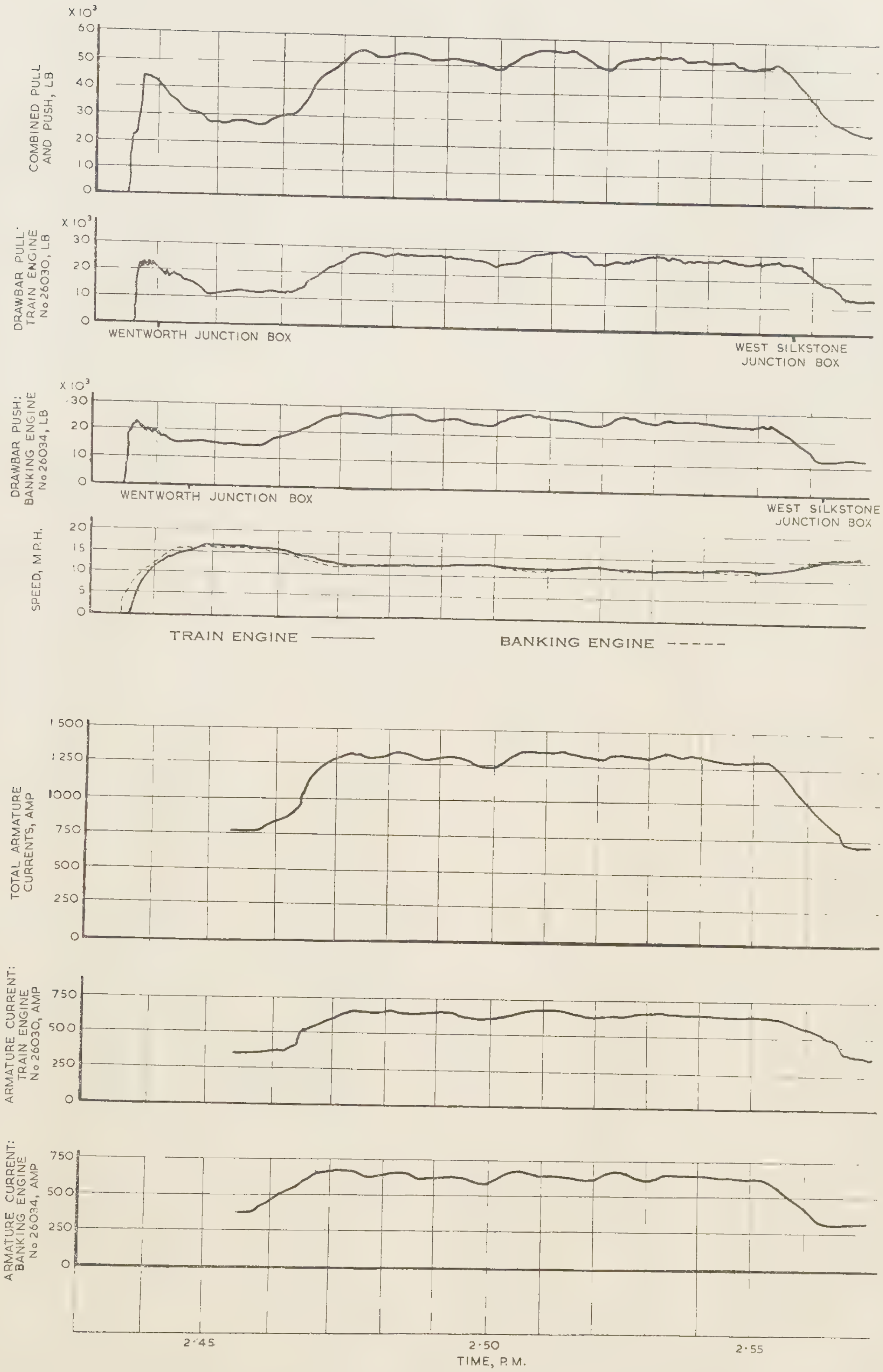



**Fig. 34.**—Records of drawbar pull and motor-armature current of Locomotives No. 26030 and 26034 (in normal condition) ascending Wentworth Bank, 20th November, 1952.

Train weight, 846·7 tons.

Since it had earlier been shown that rate of change of tractive effort had little effect on the adhesion, it had been assumed that no direct improvement in the adhesion of the locomotives could be obtained by modification of the control gear. An entirely different consideration was encountered, however, when driving with limitation of the maximum current. When starting the 850-ton train on the bank, for which a current of 680 amp was required, the notching characteristics of the locomotive control were such that each step corresponded to an increase of some 90 amp, so that the average current was considerably less than the specified maximum. A finer control would enable a higher average current to be maintained for the same maximum current, thus providing a higher average rate of acceleration with the same limiting value of adhesion, and it was naturally desired to arrange this with the minimum alteration to the existing locomotives.

A simple form of three-stage vernier resistance control was therefore designed which could be added to the locomotives with only minor modifications to the existing equipment. It took the form of a small additional control drum with three contact fingers mounted on each master controller, as shown in Fig. 35. These are connected to two contactors each of which

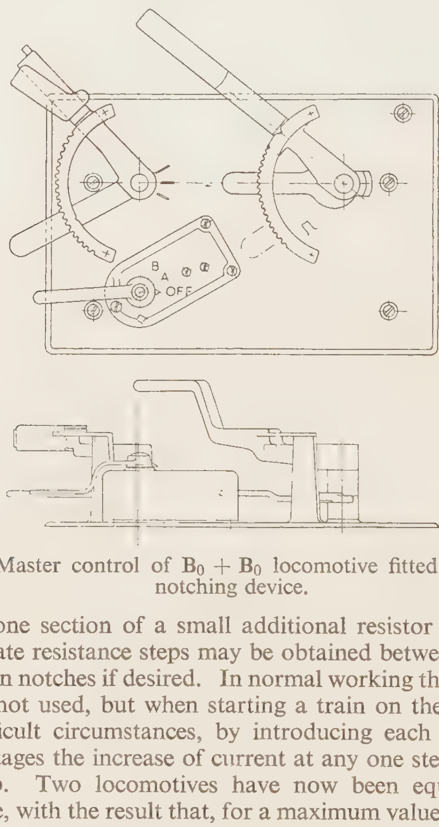



**Fig. 35.**—Master control of $B_0 + B_0$ locomotive fitted with vernier notching device.

cuts out one section of a small additional resistor so that two intermediate resistance steps may be obtained between each pair of the main notches if desired. In normal working this additional device is not used, but when starting a train on the bank or in other difficult circumstances, by introducing each main notch in three stages the increase of current at any one step is reduced to 30 amp. Two locomotives have now been equipped with this device, with the result that, for a maximum value of adhesion of 0·17, two locomotives can haul a load of 860 tons up the bank, representing an increase of 7% in the operational capacity of the locomotives.

## (8) CONCLUSION

From the preceding Sections it may reasonably be concluded that the true coefficient of adhesion at the rim of the driving wheels of an electric locomotive is affected but little if at all by the speed of the train or by the rate of increase of tractive effort, but is a function of the amount of water present on the surface of the rail and of some factor associated with the rail itself. Whether any other factor, such as corrosion of the rail surface, also affects the adhesion is at present unknown.

With the particular locomotive tested there was an appare reduction in adhesion with increase in speed which was probab due to transient changes in the axle loads which occurred wh the locomotives were exerting tractive effort. These transie changes were apparently caused by the response of the bog suspensions to the effects of abrupt changes of tractive effo of rail joints, or of other irregularities in the permanent way.

The apparent reduction of the coefficient of adhesion wi increase of speed represents a major limitation to the performan of the locomotive at higher speeds. It can probably be overcon by further consideration of the locomotive suspension in co junction with the characteristics of the electrical equipment.

Adhesion has been shown to vary between different parts the track, a feature which is at present unexplained and requir further investigation.

Employment of the "limitation of current" method of drivi on occasions of particular difficulty should considerably redu the slipping which has been experienced, and, in conjunctic with the vernier notching device, should enable greater loa to be hauled up a steep incline.

## (9) ACKNOWLEDGMENTS

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## (11) APPENDIX

### (11.1) Calculation of Weight Transfer in Motor Bogies

In any motor bogie both the load supported by the axleboxes nd the load at the tread of the wheels are affected by the tractive fort produced by the motors. For a bogie with two motor-riven axles, as shown in Fig. 36, these may be calculated in e following manner:

Consider any bogie having two axles driven by nose-suspended otors (Fig. 36). Since the weight of the locomotive body

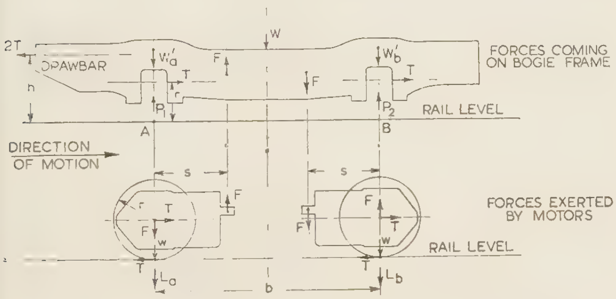


**Fig. 36.**—Calculation of weight transfer of motor bogies.

ay not be evenly distributed between the two bogies, it may be garded as two separate loads coming on the two bogies respec-vely, of which $W$ is the weight coming on the bogie under nsideration. Similarly the weight of the spring-borne portions the bogie may be regarded as two weights $W'_a$ and $W'_b$ coming the axleboxes A and B respectively, and the weight of each otor may be regarded as an unsprung portion which, together ith the weights of the wheels, axle, etc., forms an unsprung eight $w$ coming directly upon the wheel tread, and a sprung ortion coming on its nose-support which is included in the eight of the bogie.

The load coming on the axleboxes is determined from con-deration of the forces applied to the bogie frame. Taking oments around the point of contact of the wheel with the rail A, d taking clockwise moments as positive,

$$2Tr - 2Th + W\frac{b}{2} + W'_b b - P_2 b - Fs + F(b - s) = 0$$

from which $$F = T\frac{r}{s}$$

$$P_2 = \frac{W}{2} + W'_b - 2T\left(\frac{h-r}{b}\right) + T\left(\frac{r}{s} - \frac{2r}{b}\right)$$

Similarly, taking moments around the point of contact of the wheels with the rail at B,

$$2Tr - 2Th - W\frac{b}{2} - W'_a b + P_1 b - Fs - F(b - s) = 0$$

from which

$$P_1 = \frac{W}{2} + W'_a + 2T\left(\frac{h-r}{b}\right) - T\left(\frac{r}{s} - \frac{2r}{b}\right)$$

Knowing the load on the axleboxes, either from calculation or from the measured loads in the spring hangers, the total load at the tread of the wheel may be obtained by adding the unsprung weight and the reactions from the motor:

$$L_a = P_1 + w + F \qquad F = T\frac{r}{s}$$

$$= \frac{W}{2} + W'_a + 2T\left(\frac{h-r}{b}\right) - T\left(\frac{r}{s} - \frac{2r}{b}\right) + w + T\frac{r}{s}$$

$$= \left(\frac{W}{2} + W'_a + w\right) + 2T\left(\frac{h}{b}\right)$$

but $\left(\frac{W}{2} + W'_a + w\right)$ is the weighed load of the axle, $L'_a$, so, writing $K$ for $h/b$,

$$L_a = L'_a + 2KT$$

Similarly

$$L_b = P_2 + w - F$$

$$= \frac{W}{2} + W'_b - 2T\left(\frac{h-r}{b}\right) + T\left(\frac{r}{s} - \frac{2r}{b}\right) + w - T\frac{r}{s}$$

$$= \left(\frac{W}{2} + W'_b + w\right) - 2T\left(\frac{h}{b}\right)$$

$$= L'_b - 2KT$$

For the bogies of locomotives Nos. 26030 and 26034 $K$ is found to be 0·3007.

In Locomotive No. 26034 one bogie was frequently employed with only one motor in operation, in which case it may similarly be shown that

$$P_1 = \frac{W}{2} + W'_a + T\left(\frac{h}{b}\right) - T\frac{r}{s}$$

$$P_2 = \frac{W}{2} + W'_b - T\left(\frac{h}{b}\right)$$

and that

$$L_a = L'_a + KT$$
$$L_b = L'_b - KT$$

$K$ being, as before, 0·3007.

## DISCUSSION BEFORE THE INSTITUTION, 28TH APRIL, 1955

**Mr. C. C. Inglis:** Adhesion is one of the most important ngle quantities in railway working. It is, as the author said, e starting-point in locomotive design, since an engine has be of a certain adhesive weight to draw a train. It has a emendous effect on signalling layouts because of its effect on stopping distances and so on, and it has a major effect on the density of services which is possible on highly loaded lines such as, for example, the London Underground.

The paper is doubly welcome, because I have always felt that inadequate attention was paid to this problem by research

workers and by engineers. In the British Transport Commission, therefore, we have started what is called an Adhesion Committee. We knew that a fair amount was happening on the railways and in London Transport, and we thought it a good thing to start an adhesion investigation on a very wide front, using engineering, field, and research techniques, etc.

The object of the Adhesion Committee is not to undertake any work itself but to have on it those who are doing the work, so that their findings can be co-ordinated. In this way, the whole problem of adhesion from the points of view of tractive effort and braking can be surveyed. Problems can then be reviewed and investigations can be initiated if thought fit.

In starting off some little time ago we were fortunate in having available the work in the field which has been described in the paper. We have also been fortunate in that London Transport have been worrying away at this problem for some time. Thus we had a very good start, knowing that all this work was going on; but we thought it might be a good thing to widen its front.

This committee is attended by representatives of the civil, mechanical and electrical engineering departments and research departments of British Railways and London Transport. You cannot divorce adhesion from permanent-way problems. It is also attended by representatives of the D.S.I.R. and industry.

We have started a laboratory investigation of a type that is intermediate between the background work going on at Cambridge under Dr. Bowden, which is rather too far back for us, and the field work which the author has described.

Again, we were fortunate in having in the Railway Research Department what is called a tyre-testing machine, which was built some time ago. It was used in connection with certain adhesion experiments, but mainly, I think, in connection with tyre wear. That machine was lent to the Mechanical Engineering Research Organization, and Dr. Barwell has been kind enough to undertake a laboratory investigation using this machine. It was instrumented and enclosed in a box so that the atmosphere round it could be controlled. The investigation is going on at the present time.

The most striking feature of the paper is a point mentioned which I should like to emphasize again, namely variability. In the laboratory one may get a coefficient of adhesion of 0·5 under controlled conditions; in the field the variation may be 4 : 1—0·1 to 0·4—and that is a very significant pointer to the way the problems should be tackled.

If you stand by a locomotive having a.c. electric motors—the whole locomotive, when it starts up, hums and vibrates. Most of these locomotives, I think, have flexible drives, but there is no doubt that some alternating torque which must be at twice the supply frequency must get through to the wheel tread, so that the load on the wheel and rail must be varying. Has any effect due to that ever been noticed?

The author mentions various advantages and disadvantages of side-rod drives, but it has been my consistent experience that it has the great virtue of telling you when the locomotive was going to slip before it did so. That is very useful. A kind of shuddering took place, no doubt due to the oscillation of the whole system between the mass of the locomotive and the mass of the motor, the motor being connected to the locomotive through a flexible system. This shuddering occurred just before the slipping point.

One investigation we are pursuing is the rapid variation of axle loads. The apparatus described in the paper does not allow for the mass of the tyre, the mass of the wheels and the mass of the axle boxes. A wheel on a rail is vibrating, probably with a frequency between 100 and 500 c/s, and we are trying to find out whether the vibration makes any difference and whether it may explain the variation of adhesion with track characteristics.

**Mr. A. G. Hopking:** The $B_0 + B_0$ locomotives of the Ma chester–Sheffield–Wath electrification were designed in 1937– for the loading conditions of the line at that time, which involve two locomotives taking 1 074 tons up from Wath, the terminu to the bottom of the Wentworth Bank, where they had assistan from a further banking engine or engines and proceeded up t 1-in-40 gradient, at the top of which the extra bankers we dropped off. Since the war, 850 tons—as described in these tes —has been taken up by two locomotives, whereas original 1 074 tons was going to have three. Clearly conditions to-day a more onerous than those contemplated when the locomotiv were designed. The slight difficulty in co-ordinating the action drivers at two ends of the train, together with the extra loadin was largely responsible for the occasional slips that have bee mentioned.

My definition of drawbar pull is the tractive effort at the rin of the wheels of a locomotive less the tractive resistance of t locomotive itself. In Fig. 15 the curve is described as "tracti effort at drawbar." This is rather a loose description which h led to a certain error, because the author is wrong when he sa that 850 tons—which is the equivalent of 1 023 gross tons—cou be hauled up a 1-in-40 gradient with a total tractive effort 56 000 lb. This 56 000 lb is not tractive effort, it is drawbar pul and the tractive effort at a current of 675 amp is something lik 68 000 lb as, indeed, is shown in Fig. 34.

It is quite certain that a tractive effort of 56 000 lb could not pu that train up a 1-in-40 gradient, because the grade itself wou need more than that, without the train resistance in addition.

As regards Fig. 28, were these records taken with or witho resistance in series with the traction motors? The Frenc engineers are most insistent that the immunity from slippin which they get with their modern a.c. locomotives is, at least part, due to the fact that all the motors are in parallel, and n in series with each other or with any starting resistance.

Why does the author think side-rods are a good thing use with a.c. locomotives? The G.I.P. d.c. freight locomotive built in 1930 or thereabouts, were the last electric locomotiv that I remember to have side-rods. We have 3-axle Dies shunters with d.c. motors, but I think that neither a.c. nor d. locomotives with side-rods have been built for many years no for work at high speeds.

With reference to the critical speed of 30 m.p.h., on the prot type locomotive for the Manchester–Sheffield line, which w tested on the Manchester–Altringham line in 1940–41, we h synchronous pitching of the body at 24 m.p.h. This was inco venient and irritating, but not dangerous. The body was res ing on undamped helical springs, and the natural frequen of these was being stimulated at 24 m.p.h. by the relation average axle spacing of the locomotive (12 ft) to the distan between rail joints (60 ft). Only when these were taken aw and damped leaf springs substituted for the trials in Holland we we able to overcome this pitching of the body. However, think the fact that the axles are almost equidistant on this loc motive is a contributory cause in any synchronous oscillatio that has been discovered as a result of these tests.

The change in the suspension made slightly worse the tenden to slip, because there was not the same restraint against t tilting of the bogie with tractive effort.

**Mr. J. L. Koffman:** I am particularly interested in the pap since it shows coefficients of adhesion in excess of any show previously, with the possible exception of the results publish by Curtius and Kniffler. In Fig. 5 some of the points shown ha small vertical arrows attached to them, the reason being that these points the locomotive was unable to exceed the limits adhesion which in actual practice might have been higher th the values indicated by the points.

With regard to side-rod locomotives, I understood that the tests eferred to in Fig. 6 were fairly recently repeated by the Swedish tate Railways who as a result came to the conclusion that it vould be more desirable to use rod-drive locomotives, although ingle-axle drive locomotives were adopted for the Grangesberg–Dxelösund railway (TGOJ) which had to contend with very heavy ron-ore traffic. The results of the tests have shown that the dhesion maintained by rod-drive locomotives related to the dhesion of single-axle-drive units is 4 to 3. This is a rather mportant point and would seem to justify the use of the mechani-ally not very attractive rod-drive.

I was interested in the author's use of esters to increase dhesion, but I wonder whether these have any corrosive effects nd how effective they would be on snow- or sleet-covered ails.

The author states that, although he found some improvement lue to sanding, this was falling off as the speed increased. The easons for this are rather obvious, because at high speeds there vere strong possibilities of the sand being blown off before it eached the rails. In this respect I recall tests carried out on the Berlin tramways which resulted in a movable extension being rovided on the sand-feed hose which was lowered on to the rails vhen applying sand at speed, thus reducing the possibility of the and being blown off.

I think that the paper is altogether a most tactful way of howing how not to design a locomotive. It is possible that the xplanation for the design of the locomotives dealt with was, in eneral, due to the fact that they were designed as far back as 936–37. On the basis of the author's results and with particular eference to Fig. 36, showing an elevation of the bogie frame, nd referring to the effects of load transfer, it is obvious that the ractive effort should be applied in line with the centre-line of the xles, i.e. every attempt should be made to bring the centre pin ight down and in line with the axles. In addition, the buffers nd draw-gear should be positioned on the underframe and not n the bogies.

A further point is that the unsprung weight of the motor nd axle is very high and the resultant hammer blows delivered n accordance with $mv^2/2$ must be heartily disliked by the ivil engineers as well as the locomotive maintenance staff. It ppears fairly certain that the changes in load and tractive ffort recorded by the author have a lot to do with the use of xle-hung motors. When the wheel hits the rail joint it is bound o jump slightly, and the bigger the unsprung weight the harder ne blow and the longer the trajectory of the wheels jumping over ne joints, i.e. the longer the time during which the axle load on ne rails is reduced. All this tends to stress the desire for using ully-sprung motors so consistently shown by other railway uthorities.

There are two points of additional information that would be velcome. The first concerns the condition of the wheel tyres at ne time of the tests, i.e. the mileage and the shape of the tyre rofile; the other concerns the magnitude of rotational inertia f the masses concerned—i.e. the wheels and motor armature—nce these might well have a bearing on the results recorded by ne author.

**Mr. J. A. Broughall:** In introducing the paper the author said at the question of adhesion is the greatest unknown in traction. he other great unknown is how the current gets from the wire o the pantograph. These problems are equally important, articularly at high speeds, and it is possible that this should nfluence policy on locomotive testing.

We were recently discussing cases dealing with lead-sheathed ables. I recalled that most lead cables behave satisfactorily nd that we were considering the bad minority. A significant eature about locomotive adhesion is that so often it is excellent. We are seeking an explanation of the relatively few, but vital, occasions when it is poor.

The very wide variation between 0·1 and 0·4 suggests to me that a vital factor may still be eluding us. As Mr. Inglis mentioned, a much wider investigation is now in hand which may discover something that affects all the factors presently under consideration equally—something that has not yet been identified.

This is, of course, only an interim paper. The author has not mentioned that changes have been made in the particular locomotives concerned—changes in the springing, changes in the sanding, and so on—and that the tests are shortly to be repeated to see what the effect has been.

The paper does not mention the important work that has been done by the French National Railways (S.N.C.F.) who are certainly among the foremost of those who have done a great deal of valuable work on this problem of adhesion.

**Mr. A. S. Robertson:** When the author presented the curve shown in Fig. 16 for the running resistance of the electric locomotive in his recent paper on train resistance,* I commented that it was really rather high in the light of other available information, such as that of Davis† and Clarke.‡ At about 10 m.p.h. the author gives 13 lb/ton, whereas both the above authorities give about 4 lb/ton.

In general, little information is available about locomotive running resistance, probably because it is rather difficult to measure. The author appreciates the difficulty, and the results presented are based on deducing the running resistance by taking the difference between the wheel tractive effort and the drawbar pull with an allowance for grade resistance. At full tractive effort it is stated that the running resistance is only some 2–3% of the force to be measured, and moreover an error of 1% in measuring the drawbar pull would make a difference of perhaps 30–40% in the value of the running resistance. The results, however, are based on a large number of readings taken under very carefully controlled conditions, and should be reliable. The general slope of the curve conforms with earlier information and, in general, therefore, the air-resistance component is not really in question. Earlier tests might have been based largely on tests either by coasting or towing, where the locomotive is not exerting a tractive effort. A possible explanation may be that there is some difference in the running resistance between a locomotive running off-load when all the running gear is free and a locomotive on load when all the running gear is stressed, owing to tractive effort. Flange forces may well be increased owing to greater friction to turning between the bogie and the underframe, and to the pull between articulated bogies.

There is also a possibility of increased friction in the axle bearing due to tractive-effort loading. It is therefore pertinent to wonder what the results would have been had the running resistance been determined by towing.

The coefficient of adhesion shown in Fig. 19 for a dry rail is surprisingly high; up to 8 m.p.h. the average value is over 0·4. This is considerably higher than has been accepted in the past; and in two separate but extensive tests with which I have been associated it has not been found possible to work at a coefficient of adhesion appreciably more than 0·33 on a dry rail over this speed range. It is not clear from the text whether the adhesion shown in this curve is based on the measured static axle load or on the electrical weighed load on the axle boxes. The latter method is only described towards the end of the paper, but if it

* ANDREWS, H. I.: "The Measurement of Train Resistance," *Journal of the Institution of Locomotive Engineers*, 1954, 44, Part 1, p. 128, Fig. 33.

† DAVIS, W. J.: "The Tractive Resistance of Electric Locomotives and Cars," *General Electric Review*, 1926, 29, No. 10, p. 685.

‡ CLARKE, C. W.: "Notes on the Design and Equipment of a Modern Railway Dynamometer Car, from an Operative Point of View," *Journal of the Institution of Locomotive Engineers*, 1935, 25, p. 447.

Also: "Great Indian Peninsula Railway Dynamometer Car: Report No. 11 Train Resistance," 1934. Railway Board India Technical Paper No. 288.

has been included in the above curve it would explain the rather higher than normal values shown.

**Mr. D. E. Dodridge:** In Figs. 24 and 25 the author shows that the adhesion is not the same at all points along the track; I suggest, however, that he is not justified in joining these points by a curve which predicts the adhesion at points where it has not been measured.

Some of the variations in Fig. 25 may be explained as follows:

To the left of Wentworth Junction there is a fall in adhesion, due perhaps to the bouncy riding experienced just there. The adhesion increases near the $3\frac{1}{2}$-mile mark at the foot of the bank, where drivers consistently sand and where sand may be ground into the head of the rail. A little further along the adhesion again tends to fall through the tunnels where the rails are damp, while the drop at West Silkstone Junction is perhaps due to points and crossing work.

Incidentally, there is a variation in time as well as in location, and I wonder whether the author has considered this.

In Fig. 23, showing measurements made in Wath Exchange sidings, the adhesion drops at each end of the siding where locomotives are accustomed to stand, leaving deposits of oil on the track.

With regard to variation in axle loads whilst running, the motors are conventionally arranged with the noses pointing inwards. The leading axle is subject to an upward force from the suspension bearing, reducing the force available to accelerate it into rail joints, accounting perhaps for the changes in spring load when motoring which do not occur when coasting.

Has the author calculated any coefficient of adhesion using the axle load found by measuring the load on spring hangers? If not, his curves relate to a particular type of locomotive, whereas ideally a curve is required showing the true adhesion, to which are applied factors covering weight transfer, motor connection, resistance or voltage starting, notching peaks, and so on.

My last point concerns the Appendix on weight transfer. When both motors are working, it can be shown that for these locomotives the tilt of the bogies—i.e. the difference in the spring pressures—which depends on the relationship between the bogie dimensions, is practically nil. When, however, only one motor is working, the motor nose reaction must be balanced by a difference in spring pressure, and the bogie frame tilts. This tilt means that there is some influence exerted on the bogie frame from the adjacent bogie through the articulated coupling.

The effect is that, when the motored axle is at the rear, the axle loads calculated by the author are greater than the true values, and conversely when the motored axle is leading; this would increase the spread of the points in his curves, and might bias the average result, depending on the number of tests made in each direction.

**Mr. D. T. Catling:** No mention is made of the type of brake-block material on the wheels of the test locomotives. It is well known that the tyre surface is affected by the type of braking material in use on the tyre, particularly with non-metallic materials, and this in turn alters the adhesion between wheel and rail. The products of braking from the braking material can further influence the adhesion between wheel and rail by forming a coating on the tyre, and by forming a deposit on the rail in sections where braking continually occurs. For the sake of completeness I suggest that the type of braking material in use on these locomotives should be specified.

Since these locomotives are fitted with regenerative equipment, the friction-braking duties on the tyres would presumably not be comparable with those of a non-regenerative locomotive. In the author's view, has this reduction in the work done by the braking materials on the tyres had any influence on the tyre surface, and hence on the adhesion between wheel and rail?

**Mr. F. C. E. Smith:** I should like to refer to the relationship between the coefficient of friction and the amount of water on the rail. In Fig. 22 the author has shown that the coefficient of friction diminished as the rail got wetter. I should like to ask whether any time factor was considered in these results, and in particular, whether after it had been raining for some time any improvement in adhesion was noted.

In this connection, I should like to refer to some tests carried out in America by Mr. R. K. Allen. These tests show that oil deposits on a rail, even when they are not on the wheel contact surface, can produce particularly slippery conditions when small quantities of moisture are present as, for example, when dew is being deposited on the rail. It is claimed that an oil film is formed by displacing this condensed water which leaves a very greasy surface that will resist any further wetting with water. This oil film will, however, be destroyed by heavy rain, when the coefficient of adhesion will be improved.

Referring to methods of improving adhesion, the extensive use of sand can give trouble with the signals, owing to bad contact on the track circuits, particularly when rail cars also use the same route. The experiments with the ester solutions are therefore very interesting and no doubt the results will warrant the development of special equipment to deposit the solution on the rail.

**Mr. R. Ledger:** If an adequate electrical rating is assumed, the weight of train which a type of locomotive can be permitted to work over a route is determined by the lowest coefficient of adhesion obtained under normal service conditions. The tests described in Section 7 established a limiting value of 0·17 for these locomotives, giving a maximum train weight up a 1-in-40 gradient, using two locomotives, of 800 tons. This loading appears to be somewhat lower than is obtained elsewhere using single locomotives or locomotives working in multiple under the control of one driver. Could the method of working with a locomotive at each end of the train, each being under independent control, be partly responsible for this?

Would it be possible to include in any future investigation tests on other types of electric locomotive now in service on British Railways, as these would be useful in showing the effect of factors such as excessive variation of axle load peculiar to a particular class of locomotive?

**Mr. E. W. Curtius** (*Germany: communicated*): Naturally it is better to increase the tractive effort by gradually regulating the motor voltage to make the axle slip, as was done during the tests of British Railways. In Germany we increased the tractive effort under constant motor voltage by increasing the braking effort so that each time the speed naturally fell. This method had to be used, otherwise a great rearrangement of the circuits of our a.c. locomotive would have been necessary. Because the task at that time was to investigate the high-speed zones (more than 80 m.p.h.), only one type of locomotive existed that could produce the torque necessary for slipping. In principle, however, the tests were similar to the British ones.

The German locomotive had no bogies, but a rigid frame. The single slipping axle was not connected mechanically with the other axles in the frame, and the tractive effort could not therefore be influenced by the weight transferred from the other axles. At that time we had no instruments for measuring loads on axle-boxes. Such instruments, however, are frequently used.

The explanation of the great spread of the adhesion values by finding a dependence between adhesion and the location—i.e. special condition of the rails—is very interesting. I believe, however, that the higher values are also produced by the roughening effect of dampness, i.e. corrosion. Such an effect might be similar to the described influence of ester solutions, increasing the adhesion values. Finally, it is possible that the different conditions of the rim surfaces after hard braking may influence the adhesion

## THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

**Dr. H. I. Andrews** (*in reply*): While all the observations described were made on d.c. locomotives having individual drives, it is interesting to consider what corresponding effects would be obtained with either a.c. locomotives or locomotives having coupled axles. Thus, as Mr. Inglis points out, it is inevitable with a.c. locomotives that some measure of variation in the tractive effort must reach the driving wheels, yet it is often claimed that a.c. locomotives have better adhesion characteristics than d.c. locomotives. Similarly, the improvement in adhesion, shown in the Swedish experiments, obtainable with coupled locomotives is difficult to explain, although it is now understood, as mentioned by Mr. Koffman, that this conclusion has been re-verified in further investigation, and it is to be noted that certain heavy goods locomotives recently put into service by the Swedish Railways are fitted with coupling rods. These considerations certainly demand further investigation, and while both natural and induced vibration at the wheel track have probably an effect upon adhesion, it is by no means certain that this effect is detrimental. An account of the measurement of stresses in the coupling rod of an a.c. locomotive has been given by Houston and Wheeler.*

The term "drawbar pull" sometimes gives rise to confusion, and its use has therefore been avoided unless the actual force passing through the drawbar is implied. For an electric locomotive the nominal tractive effort at the wheel rim is the sum of the tractive efforts of the motors, as determined from their actual characteristics obtained from tests with gears, and from the actual diameters of their wheels. From this must be deducted the mechanical resistance associated with the driving axles, which, for a locomotive employing all its wheels for traction, at low speed and low wind velocity, may be taken as the total resistance of the locomotive shown in Fig. 16, which leaves the actual value of tractive effort available at the rim of the wheels—the value used in calculating coefficients of adhesion. From this again must be deducted the effects of gradients on the locomotive, leaving the tractive effort at the drawbar or the "drawbar pull." The figure for tractive effort applied to the train in the calculation in Section 7, mentioned by Mr. Hopking, is therefore the sum of the "drawbar pull" of the leading locomotive and the "buffer push" of the following locomotive, and represents the actual force applied to the train proper. The observations shown in Fig. 28 were obtained with no resistance in the motor circuit, and it might reasonably be claimed that the incipient slips were being stifled by the motor characteristics in the manner described by Royer.[8]

The ester solutions referred to by Mr. Koffman usually contained only 1% or less of ester, and could generally be regarded as only tainted water. They are thus unlikely to cause any appreciable corrosion of the rails and, presumably, in cold weather the discharge of warmer solution could only be beneficial on rails covered with sleet or snow. Bogies designed on the lines suggested by Mr. Koffman have actually been used in France, and it is claimed that, by these means, difficulties connected with weight transfer are reduced. The tyres were in slightly worn condition throughout the tests, and the rotational inertia of the motor armature and pinion was about 1 020 lb/ft$^2$; that of the wheel and axle assembly was 10 700 lb/ft$^2$.

As Mr. Broughall has pointed out, it appears from Reference 8 that some investigations on these lines have been carried out in France, as a result of which it has been found possible to obtain improved adhesive performance from certain types of locomotive, but unfortunately no details of these investigations seem to have been published.

The resistance values measured on Locomotive No. 26030, shown in Fig. 16, mentioned by Mr. Robertson, are certainly higher than were expected, but they were corroborated by the figures obtained from both locomotives hauling trains up the bank. That certain rather high values of adhesion were recorded is due to the fact that, in this investigation, the locomotive was compelled to slip at each test, however difficult this might be, whereas in some other investigations observations were made only on slips occurring naturally.

Mr. Dodridge has made a number of valuable suggestions which explain some of the observations of adhesion, but not others. So far it has been impossible to determine all the factors influencing these results; only those factors for which a definite relationship can be established have therefore been mentioned in the paper. Thus the observations in Fig. 25 were plotted to demonstrate the fact that there is some relationship between adhesion and location, and curves have been drawn to illustrate that relationship. Doubtless most values determined in intervening positions would also fall on these curves, but there is no reason why different values should not occur with any irregularity in the condition of the track.

In reply to Mr. Catling, the brake-blocks were of cast iron, and regenerative braking was used only during the descent of the Wentworth Bank. It is therefore probable that the remaining service braking, for which the locomotive air brakes were used, would be about normal for this class of traffic. Contrary to expectation, no appreciable improvement in adhesion could be detected after continued wetting of the rails.

Since it is essential to have one locomotive at the rear of the train for braking purposes, it would be impossible for these locomotives to be worked in multiple unit, and it is therefore possible that lack of co-ordination between the drivers may result in some loss of adhesive performance. This difficulty may be substantially overcome, however, by the use of the limitation-of-current method of driving, since in this case the adhesion load is equally shared between the two locomotives.

The communication from Mr. Curtius, whose previous work has been described in the paper, is of great interest, particularly the suggestion that adhesion may be increased by corrosion. It has been found in the laboratory that very high values of adhesion can be obtained on rusted rail surface, even if the rust has been very quickly produced, which appears to corroborate the views of Mr. Curtius.

Owing to the complexity of the adhesion problem and our limited understanding of the nature of friction, any investigation of this type must be exploratory, so that when a relationship has been established between adhesion and any of the factors involved, it must be recorded and an explanation sought. The relationships so far determined have therefore been presented with only such comments as have been directly derived from the experimental results. The investigation was carried out in the order described, so that all values of the factor of adhesion quoted are based on the nominal value of the axle load, the measurement of actual axle loads being in the nature of a subsidiary investigation undertaken to explain certain apparent discrepancies in the results. Naturally, in any further work the actual values of axle load must now be determined and used in calculating adhesion values. As mentioned both by Mr. Broughall and by Mr. Inglis, the work is being continued, and it was decided that the results so far obtained should be published at this stage to obtain the benefit of the comments of other workers in this field.

* Discussion on paper by Lowenberg: "Stresses in the Drive System of Three-Cylinder Locomotives," *Transactions of the American Society of Mechanical Engineers*. APM–50–13.

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# THE SUPPLY OF ELECTRICITY IN THE LONDON AREA

By D. B. IRVING, B.Sc., Member.

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*the* SUPPLY SECTION, 18*th May*, 1955.)


## SUMMARY

This is essentially a survey paper. It endeavours to present concisely a clear view of the many, sometimes conflicting, influences which have conditioned the supply of electricity in London from the beginning. Particular regard is given to the activity of the enterprise which has the privileged task, for the first time, of controlling London's electricity comprehensively.

The paper presents the information in logical and, where appropriate, chronological sequence, although much of significance has had to be lightly passed over for the sake of brevity. It is shown that savings in capital and operating costs are already resulting from action on a centralized assessment of the London problems, as is enabled by the Electricity Act of 1947.

The overall electrical efficiency has been improved and will become even higher as the replacement of old non-standard systems is hastened.


## (1) INTRODUCTION

The expression "London Area" is ambiguous, unless further definition is provided. Before the Metropolis Management Act in 1855, the expression denoted only the City of London with certain other areas loosely bound to it, as Southwark which was allied to the City (as Bridge Ward Without) by Edward III in A.D. 1327, and small parts of what is now the City of Westminster. In 1888 the London County Council was established to administer an area of 117 square miles. In 1936 the McGowan Report[1] suggested the preparation of a scheme for the improvement of electricity distribution in the Greater London Area. The Electricity Act of 1947, however, determined a more limited area, of some 257 square miles, to be the "London Area" for electricity purposes. It is this Area to which the paper refers.

Among the 14 Electricity Board Areas created under the 1947 Act that of the London Board presents some special characteristics. Its size is less than one-tenth of the next smallest Area, but its average density of population is more than 20 times that of any other Area. Operating in the London Area prior to Vesting Day (1st April, 1948) were 30 municipal undertakings and 11 company undertakings, one of which had no distribution rights.

Although the unification of London's electricity supply was finally achieved as part of a national operation not entirely uninfluenced by political forces, it had long been realized that, technically and economically, such a unification possessed the possibility of much advantage.

## (2) HISTORY

### (2.1) Origins

The special position of London as the capital of an extensive and prosperous empire caused it to be the scene of a scramble for powers and areas of distribution unmatched anywhere in the world in the history of electricity supply. Under the first Act relating to public electricity supply, that of 1882, some 32 provisional orders were granted for London, of which no fewer than 25 were revoked in two years' time. Some of the early companies started operation without statutory powers, for the 1882 Act was concerned mainly with powers to break up the streets to l mains. Such companies laid their mains in existing subwa or overhead, and so evaded the provisions of the Act.

Of the companies which did apply for provisional orde several were already giving supplies and in no case was operati long delayed. The municipalities, using public funds, had, necessity, to proceed more cautiously, and delays occurre amounting to years in some instances, between the granting an order to a municipality and the provision of a supply.

In several districts Parliament sanctioned more than o undertaking, the reason usually being that one was an a.c. a the other a d.c. protagonist. The consumer was to be allow freedom of choice. In a few localities three different enterpris obtained powers and, with true British lack of logic, so important places like Staple Inn, Lincoln's Inn, and the pari of St. Peter, Westminster, were not mentioned in any lighti order.

In some districts where company undertakings overlapped t disadvantages soon became apparent and after a time so mutual arrangements were made which rationalized conditio in small parts of the Area. Several London companies combin to provide their generation requirements by a bulk supply co pany as early as 1902, and again, on a larger scale, in 1925. A amalgamation of six West-End companies in 1937 was a furth important step in the rationalization of supply administrati and systems within the six square miles of that part of the Are

The municipal and company areas of supply as they exist prior to Vesting Day are shown in Fig. 1.

### (2.2) Legislation

The Electric Lighting Act of 1882 was the first Act of Parliame relating to electricity supply, and it is of interest to note that, this and subsequent Acts, ultimate public ownership of t supply industry was envisaged. The Act of 1919, under whi the Electricity Commission was established, resulted in t defining of a London and Home Counties Joint Electrici District within which all company undertakings were to transferred in 1971 to a Joint Electricity Authority.

Acts of 1925 made provision for closer association betwe many of the London companies. Ten of them combined th generating resources to form the London Power Company, a the County of London and City of London Companies arrang for closer co-operation.

The Central Electricity Board was created by the Act of 19 to rationalize the generation of public electrical energy on national basis. It successfully accomplished this task by t construction of the national 132kV Grid system and the inte connection and control of generation. The cost of the Gr system was more than recovered by the resulting substanti reduction in spare-plant investment and by operational economie The Central Board did not own the generating stations but wi a small staff directed the operating programmes and purchas the whole of the output. Such quantities as were required generating undertakings for the purpose of supplying their ov distribution systems were resold to these concerns. The requir ments of non-generating undertakings were met from the surpl

Mr. Irving is with the London Electricity Board.

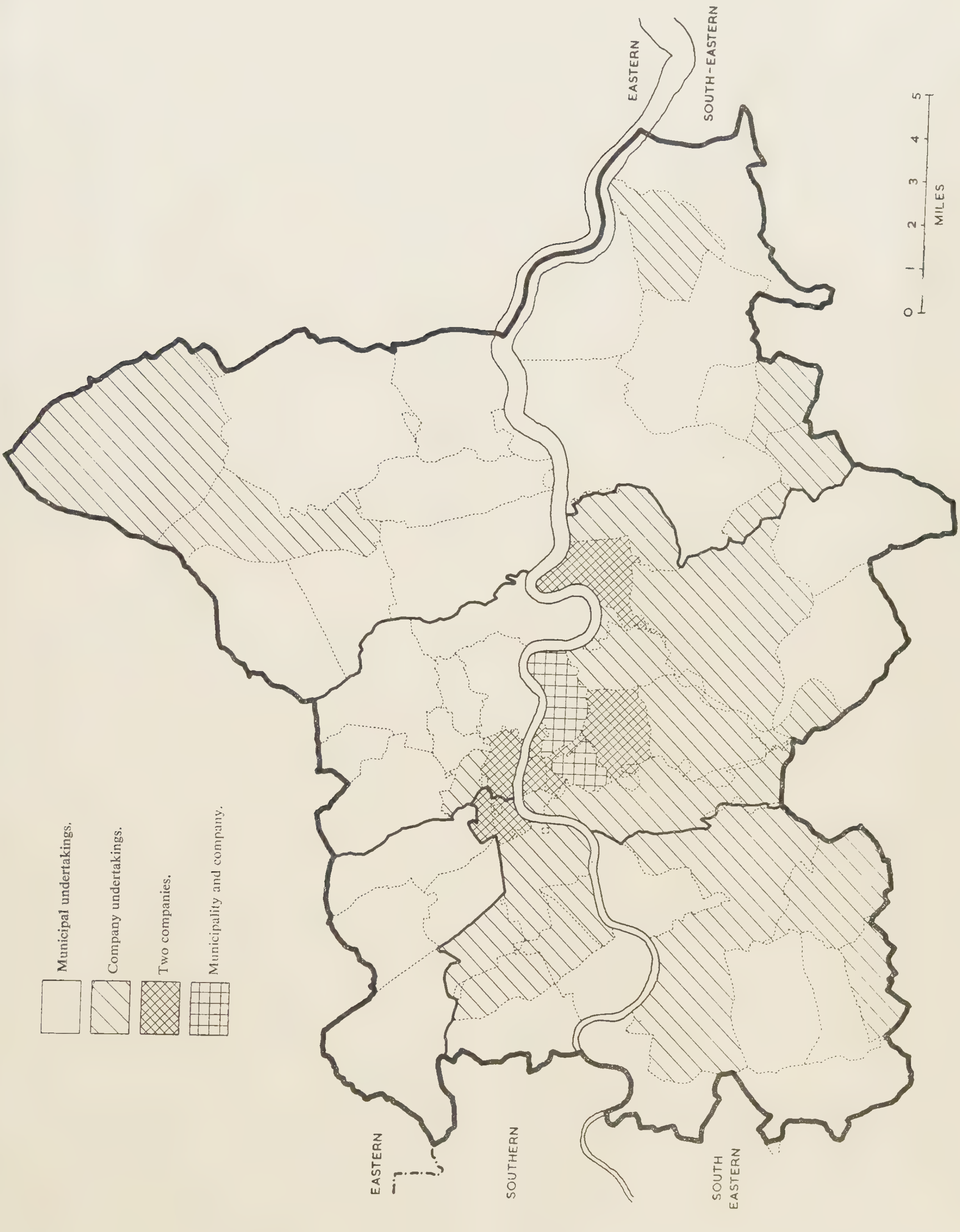


Fig. 1.—Municipal and company areas.

capacity of the stations and the national Grid. The Act assured equitable treatment of any undertaking which could show that it could generate for its own purposes at a cost lower than that payable under the prevailing standard "Grid tariff." These methods of operation caused much controversy, but, in fact, the Central Board served the industry well for some 21 years.

In 1947 the Act was passed under which the whole of the industry was nationalized. It established the British Electricity Authority and 14 Area Electricity Boards. Ownership of generating plant and the Central Board's Grid system passed to the Authority, whose prime task was to be production. The distribution assets of the various undertakings vested in the Area Boards.

### (2.3) Production of Electricity in the London Area

As early as 1881 a public lighting supply was given by the Anglo-American Brush Company, from their station in Belvedere Road, Lambeth, to light some of the streets in the City of London. This continued for some years as a non-statutory supply. From 1882 onwards several non-statutory companies began generation for the lighting of special areas, e.g. Holborn Viaduct and Kensington Court, and in 1883 the Coutts Lindsay Company began a non-statutory supply from the Grosvenor Galleries station. In 1890, its successor, the London Electric Supply Corporation, started to supply from Deptford. In 1891 the City of London Electric Lighting (Pioneer) Company was formed as a statutory company and put down stations at Wool Quay in Lower Thames Street, and at Bankside on the South Bank. Wool Quay was shut down in 1898, the plant having been previously transferred to Bankside in the course of time.

The first station at which turbo-alternators were installed was the Manchester Square Station of the Metropolitan Company. Commissioned in 1894, the sets had an output of 350kW at 1 000volts, 100c/s, and 3 000r.p.m. The oldest generators at work in 1954 were at St. Marylebone. They are d.c. machines, commissioned in 1905, having a capacity of 2 000kW.

To-day the London Division of the Central Authority operates 28 power stations of an aggregate capacity exceeding 3 250MW, supplying London and parts of adjoining Areas, and ranging in size from 750MW at Barking to 3MW at Shorts Gardens, in the West End. The latter, though small and a d.c. station, makes its welcome contribution to peak loads.

The plant at Shorts Gardens is the sole remaining example of internal-combustion plant on public supply in the Area, and is the only one generating at the utilization voltage of 210 volts. Other generation voltages range from 5·2kV at St. Pancras to 33kV at Taylors Lane, Willesden.

### (2.4) Transmission and Distribution

The history of the high-voltage cable systems in London is the history of power-cable development.[2] As early as 1887 there were some 16 route miles of rubber-insulated cables operating at 2 400 volts and strung upon poles and roof-top insulators in the West End. S. Z. de Ferranti then boldly initiated transmission at 10kV from a riverside power station, seven miles distant from London, transmission to the West End being effected by tubular copper paper-insulated mains which he designed and manufactured at the power station.

British cable makers soon produced flexible paper-insulated cables for this voltage, and 3-core 11kV cables were laid in the area in 1901, followed in 1905 by similar cables for operation at 22kV. In 1910 there was installed on the Thury d.c. system from Willesden a single-core cable suitable for operation at 100kV, and this was at work until 1924. Some belted cables made in 1923 for 33kV operation were not successful and had to be derated to 22kV. At this voltage they have given satisfactory service up to the present time.

Screened cables in 1927 for 33kV working were succeed by 66kV single-core screened cables in 1930. This year s also the introduction by the Central Electricity Board London of the 132kV single-core oil-filled cable. Two yea later a 66kV 3-core pipe-line compression cable system w laid between Hackney and Walthamstow, and in 1937 a sing core 132kV cable circuit of the pre-impregnated pressure ty was installed at Wimbledon.

From that time onwards various types of gas-pressure cal appeared in the London Area for operation at voltages up 132kV, some of these being among the first of their type to used anywhere in the world. One 5-mile-long 33kV impregnat pressure cable has an aluminium sheath. Another, of the 3-co 132kV impregnated pressure type, which has a maximum desi stress of 100kV/cm, was recently installed between Barki and Ilford.

Accompanying the early h.v. cable developments the ha hazard growth of distribution systems proceeded apace, a to-day there are to be found still in operation networks of ba copper strip in culvert, cables in vulcanized bitumen, plain lea covered cables in cast-iron pipes, as well as the later systems drawn-in and direct-laid armoured cables. The complex patte of the 40 distribution systems inherited by the Board includ single-phase, two-phase, three-phase, and direct current, with n fewer than 20 distinct voltages of utilization between 100 an 500 volts. High-voltage systems operating at 18 differe voltages between 1kV and 11kV also existed.

Quite apart from standardization, the inadequacy of most these old systems was such that at Vesting Day the Lond Electricity Board were faced with heavy capital expenditure many of their Districts.

## (3) TECHNOLOGY

### (3.1) High-Voltage Systems

The 132kV overhead and underground interconnections in t Area are operated by the London Division of the Central Authori

The high-voltage systems of the London Board consist entire of underground networks operating at 66kV, 33kV and 22k Networks operating at 11kV and below are thought of, to-da as distribution networks. The 66kV and 22kV systems former operated by the London Power Co. lie almost wholly within t Area now served by the London Board. Others at 66kV, 33k and 22kV, which were operated by the County of London Co were designed to supply a group of associated companies, so of whose areas lay outside that now served by the Boar Another system at 22kV was operated by the Woolwich Borou Council.

The London Power Co.'s main station was at Battersea, the south-west, and the County Co.'s main station was Barking, in the east. The growth of the demand from t respective constituent companies was such as to cause t London Power Co. to run transmission circuits eastwards on large scale, and the County Co. to run circuits westwards an south-westwards, with consequent overlapping. Had simil operating voltages been adopted, the marrying of the system after nationalization, to meet future demands, would ha been simplified.

It was a fortunate circumstance, of which advantage wa quickly taken, that the communication circuits of the Londo Power Co. could be readily diverted into the County Co. communication system, and the Valley Road control centr established by the latter company at Streatham, has becom London Distribution Control.

The transmission problem which confronted the Londo Board at Vesting Day is evident from Fig. 2, which shows t main circuits in operation in the Area.

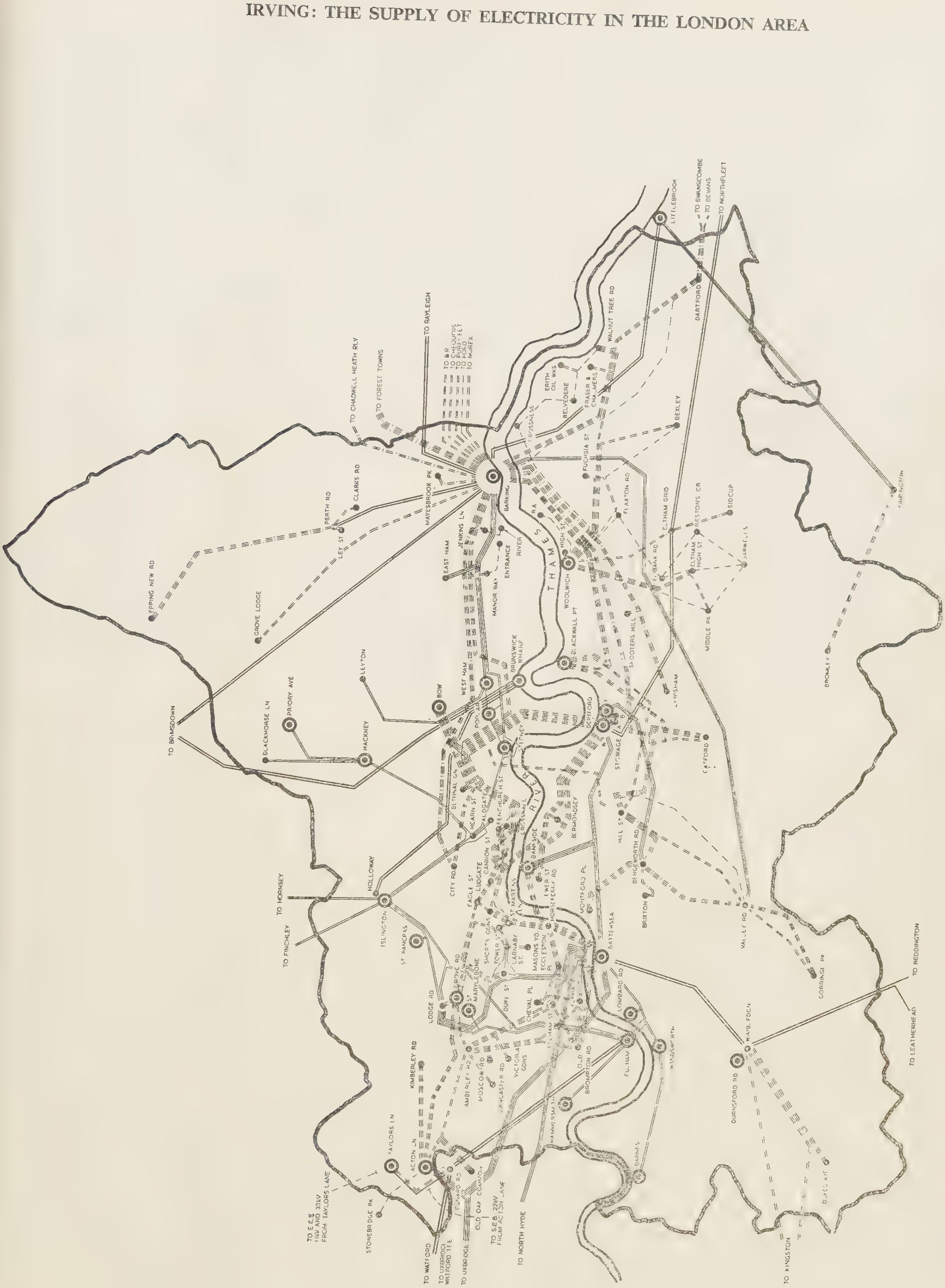

Fig. 2.—Main circuits in the London Area: 132kV, 66kV, 33kV and 22kV.

Generating station.
Substation.
132kV circuit.
66kV circuit.
33kV circuit.
22kV circuit.

With the renewed impetus in the growth of load after the 1939–45 War, the need for reinforcement of bulk supplies at many points became extremely urgent. This would not admit of the delay inherent in the detailed assessment of the whole London position and the subsequent preparation of the Board's long-term plans for the Area. It was necessary, therefore, to plan and construct the more urgently needed reinforcements concurrently with the formation of long-term plans.

In this work the Board's engineers maintained close liaison with those of the Central Authority, since much of the Board's work had, of necessity, direct repercussions on the Authority's systems. The technical and economic merits of many short-term schemes were evaluated, and it was agreed to adopt the most economic scheme of reinforcement which was technically suitable, irrespective of the division of the total capital expenditure between the two parties.

One of the cardinal principles on which the Board's long-term plans are being founded is that of reducing to the minimum the distances over which bulk supplies are transmitted within the Area; this principle has been borne in mind by the engineers in making their recommendations on the short-term urgent schemes. It will not, however, be possible to attain the ideal transmission system, since all technical considerations are governed by the need to utilize to the full, within economic limits, the mosaic of transmission equipment inherited by the Board at Vesting Day. Compromise has therefore been necessary, but, despite this, substantial savings on transmission within the Area, as compared with what would have been expended under the pre-nationalization arrangements, have already been made.

Thus, to take only one instance, a new 66kV substation in South-West London,[3] having an installed capacity of 150MVA, is supplied with energy from a power station some eight miles nearer to it than the one from which it would have received its supplies in the circumstances prevailing before Vesting Day. This has resulted in a capital saving on the 66kV cable routes of three-quarters of a million pounds and a recurring saving in transmission losses of some £35 000 per annum. Such savings will increase as the Board's plans mature in the future. One of the features in the Board's plans is the extended use of e.h.v. transformer feeder circuits to economize in the use of switchgear.

### (3.2) Substation Equipment

Voltage reduction from 66kV is effected at seven major substations having a total installed transformer capacity of 500MVA. These, in turn, feed certain main substations at 33kV and 22kV, where the voltages are further reduced for distribution mainly at 11kV. In the main substations, of which there are 72 throughout the Area, the installed capacity of the transformers totals 2 263 940kVA.

The number of local substations and transformer chambers, whether in buildings, kiosks or underground, for reducing voltages to supply medium- and low-voltage networks, is 7 128, with an installed transformer capacity of 3 535 638kVA. At some substations single-phase and two-phase supplies are given from three-phase systems by Scott-connected transformers, and at others d.c. supplies are furnished by means of rotary plant and mercury-arc rectifiers.

In system design and operation to-day, every effort is made to keep prospective short-circuit duties at the different parts of the system within limits that will permit the use of switchgear of the following breaking capacities:

At 66kV, 1500MVA; at 33kV, 750MVA; at 22kV, 500MVA; and at 11kV, 150MVA.

The adoption of these ratings was governed largely by the presence in the system of switchgear which it would be completely uneconomic to replace. In certain parts of the system it has not been possible to keep the duty down to 150MVA : 11kV, and in these instances 250MVA switchgear is used. O the standard 415/240-volt networks the maximum value of th short-circuit duty is 25MVA.

In the seven major substations which are supplied at 66kV th transformer units range in size from 15MVA to 50MVA. A the 72 main substations, supplied at 33kV and 22kV, the size range from 3MVA to 20MVA. Up to about 15MVA, trans former units are oil-immersed with natural air cooling. I certain localities, however, to obviate disturbance due t transformer noise, units have had to be almost totally enclose and the restricted ventilation has necessitated the installation o forced cooling on some units rated at, or less than, 15MVA Above 15MVA the units are oil-immersed with natural a cooling up to about half full load, and when operating at highe loads they are cooled by forced oil circulation and supplementa air blowing.

Most of the bulk-supply transformers now being installed ar fitted with on-load tap-changing mechanisms having a 20% range of regulation, but there are a number of variants accordin to the winding connections and the local conditions existing i the different Districts prior to nationalization.

### (3.3) High-Voltage Distribution Cables

Many distribution systems had been neglected during th Second World War, and the return of evacuated population an recovery of normal industrial activity accentuated the need fo replacement of obsolete systems and for reinforcement of th more modern standard systems. The urgency of the need wa responsible for a decision to regrade to a higher voltage man h.v. distribution cables, some of which had already given yea of good service at the lower voltages.

Regrading from 6·6kV to 11kV has been effected in te Districts, from 5·2kV to 6·6kV in two Districts, and fro 5·2kV to 11kV in one District. In yet another District, cable have been regraded from 3·8kV to 6·6kV.

Paper-insulated lead-covered cables, properly installed, hav proved themselves to be among the most reliable of all items o electrical plant. Cables manufactured to B.S. 7: 1926 for 6·6k are working satisfactorily at 11kV. Some gloomy foreboding concerning the vulnerability of joints have, so far, been unfounde

### (3.4) Medium-Voltage Non-Standard Systems

The Electricity Act, 1947, Section 6(*e*), charged the Londo Board, in common with other Boards, with the duty of pro moting the standardization of systems of supply. Standardiza tion is proceeding, but in 1954 the maximum demand carried b the Board's systems still included components of direct curre (8·9%), 2-phase alternating current (2·2%), and other non standard alternating current (22·7%). The Board has 170 00 consumers on d.c. supplies, and 627 000 on non-standard a. supplies, the standardization problem in the London Area bein considerably larger than that of any other Board. Althoug London has no rural problem it is estimated that the total co of system change-over, at prevailing prices, will be about £5 million. Unless the present rate of progress, in which 37 00 consumers were changed to standard supplies during 1953–5 substantially increases, the achievement of complete standardiza tion will take many years. Present policy is governed by restri tions on capital expenditure, and attention is necessarily focuse upon overloaded non-standard systems.

### (3.5) Medium-Voltage Systems: Rationalization

Since practically the whole of the Area is built up, and as whole may be considered to be densely loaded, the principl

upon which the Board's doctrine of rationalization is founded are to a large extent those applicable to the City and West End described by Leach[4] in 1941. Present-day costs unhappily bear little relation to those given in that paper.

The system described by Leach consisted, in its essentials, of unit areas based on bulk supply points of 48 MVA capacity, fed from a transmission system operating at 22 kV and higher voltages. The typical bulk supply point was designed for an ultimate installation of four 12 MVA transformers feeding up to four sections of 11 kV busbar, normally operated singly or in pairs.

The h.v. feeders were laid out as ring mains but operated as radial feeders, thus permitting the use of simple over-current and earth-fault protection. The l.v. distributors were uniform in section and were laid along each side of the street, covering all the frontages over which there is a statutory obligation to provide supplies. The l.v. network was interconnected "solidly" in sections corresponding to the h.v. feeders and by fuses over a district corresponding to 12 MW, four such self-contained districts comprising a 48 MW unit, all on a basis of 25% or less spare capacity.

The 500 kVA transformer chambers, situated mainly in consumers' premises, were equipped with h.v. "ring main units" having an automatic oil circuit-breaker in the tee with over-current and earth-fault protection for the transformers. Between the l.v. side of the transformer and the interconnected l.v. network there was an air circuit-breaker fitted with oil time-delayed over-current protection and intertripping.

The arrangement reaps a great advantage from diversity of demand with minimum losses and affords high continuity of supply, owing to the standby afforded by the l.v. network interconnection in the event of failure of h.v. feeders or local transformers.

Another system of supplying an interconnected l.v. network was referred to by Webb in the discussion on a paper by McLean.[5] In this system the h.v. switchgear is simplified by omission of the automatic oil circuit-breaker and the use of a plain tee connection to the purely radial h.v. feeder. The distribution transformers are "interleaved" and the network protector between the transformer l.v. side and the l.v. network is motor operated, the operation being controlled by a combined reverse-power and auto-reclosing relay. The extent of the l.v. network regarded as a busbar is very much larger than any previously used in Great Britain, but similar systems have been in use in the larger cities of the United States and in Germany for many years. Figs. 3 and 4 illustrate the connections.

This arrangement offers opportunity for considerable economy where outdoor construction can be made to fit in with the amenity requirements of planning authorities. The accuracy

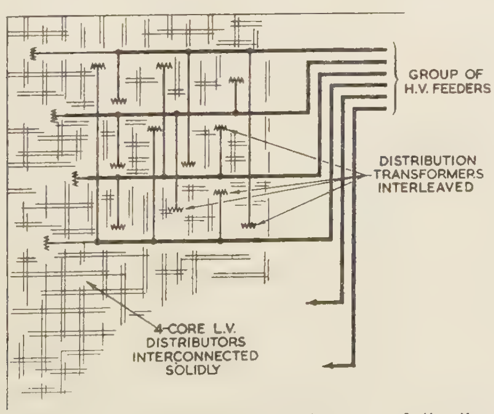


Fig. 3.—Radial interleaved scheme: diagram of distribution.

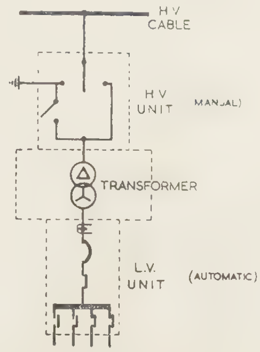


Fig. 4.—Radial interleaved scheme: diagram of transformer unit with h.v. and l.v. switchgear.

with which the load can be forecast and the local building requirements are factors difficult to assess in estimating the financial results, but in one District of the London Area where an extensive change-over from single-phase to the standard 3-phase system is being undertaken the technique and economics of this system are being given a thorough trial. The present maximum demand in this District is 33 MW, and this is expected to double in the next ten years. The section of "solid" network will carry about 20–25 MW and the h.v. oil-immersed switches and the l.v. network protector equipment will be outdoor weatherproof units fitted to the transformer tank. Buildings to house the units will be required only where amenity considerations dictate the practice, and in many installations it will suffice to place the transformer unit on a concrete raft enclosed by fencing. Fig. 5 shows the arrangement of such a transformer unit. The estimated total capital cost of the complete work on this 11 kV and medium-voltage system to provide for a 60 MW demand in the District concerned in about ten years' time is just under £2 000 000. The cost per kilowatt is believed to be lower than that to be incurred by any other type of high-load-density system capable of affording equivalent service.

It is emphasized that these "solid" systems have a proper economic application only in cities where the load and consumer density is high. In parts of Central London the load density is already in excess of 100 MW/square-mile and is expected to approach 200 MW/square-mile within the next 15 years. There is wide scope for application of these interconnected systems within the Area where load densities are little influenced by very large individual consumers.

The proportions of the total units supplied in 1953–54 which were taken by the different classes of consumer are shown in Fig. 6.

## (4) STANDARDIZATION

### (4.1) Engineering

One of the more obvious ways in which centralized direction might be expected to improve efficiency is in bringing about some standardization of engineering principles and practice. The Board recognize, however, that standardization cannot be achieved overnight, nor must it be permitted to impede progress; the merits, both technical and economic, of the various systems which might have application under London conditions are kept constantly under review. With the heterogeneous collection of approaches to engineering problems inherited from 40 unrelated distribution undertakings it has been necessary to make haste slowly.

At an early stage the Board decided upon the distributed transformer system with a standard transformer capacity of 500 kVA, and new extensions authorized were required to make provision for ultimate development on those lines. A limited

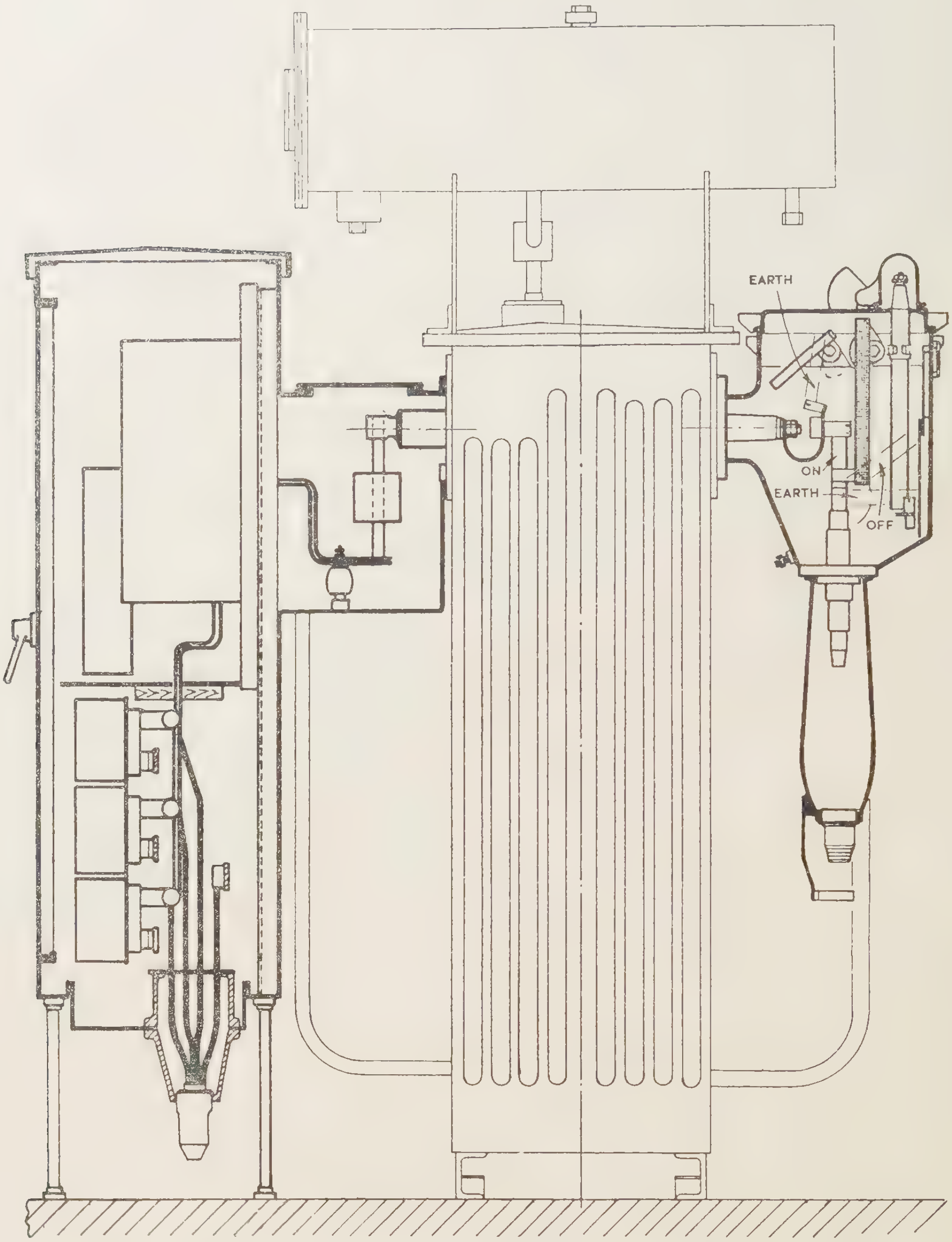


Fig. 5.—Radial interleaved scheme: assembly of transformer and switchgear units.

range of standard cable sizes and a standard range of meters were also adopted.

In the larger substations the trend towards eliminating, on economic grounds, continuous attendance has made it desirable to provide for more automatic features in the operation of the main transformers. The typical size of these is now 15 MVA, with sufficient reactance to retain general fault levels in the 11 kV distribution systems at 150 MVA and in special cases up to 250 MVA.

In view of the large amount of capital invested in service apparatus and service cables, standards for services were also laid down towards which future effort was to be directed.

Four types were delineated:

"*Small*" *Service*.—For small, isolated loads, e.g. telephone kiosks, signs, public lighting. The cables used are vulcanized

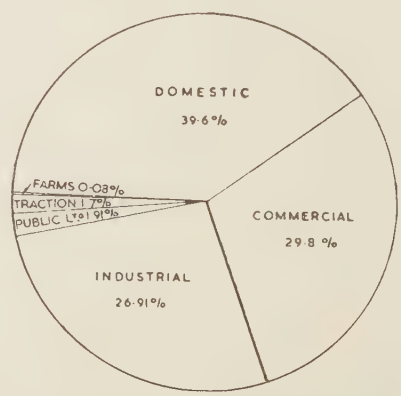


Fig. 6.—Proportions of total energy supplied to different classes of consumer, 1953–54.

rubber insulated (v.r.i.) or paper-insulated lead-covered (p.i.l.c.), $0 \cdot 007\,\text{in}^2$.

"*Normal*" *Service.*—For use at most domestic and shop premises. Twin or 4-core p.i.l.c. cable, $0 \cdot 0225$–$0 \cdot 06\,\text{in}^2$.

"*Large*" *Service.*—For use where the load exceeds the capacity of the "normal" service. Four-core p.i.l.c. cable, $0 \cdot 1\,\text{in}^2$.

"*Transformer Chamber*" *Service.*—For supplies direct from a transformer chamber, or in special cases from the medium-voltage network. Four-core $0 \cdot 3\,\text{in}^2$ cable, or four single $0 \cdot 3\,\text{in}^2$ cables.

Much detailed standardization of individual items of stores and equipment is being achieved by a standing committee of the Chief Engineer's Department, on which all departmental interests are represented.

The principle of using the earth grid of the sheathing of the supply cables to make an earth connection for the casings of the consumers' installations is admitted where it is known that such sheathing is adequate and electrically bonded throughout. Several networks still exist, however, on which bonding is non-existent or suspect, and thus the use of the Board's earthed grid must always be subject to local determination.

### (4.2) Procedure

The Board has also standardized the procedure for connection, disconnection and supply of energy to consumers' installations, with stress being laid on inspection and testing. In London, in which there are some half a million prepayment meters, changes of tenancy without disconnection of supply are frequent, and it has been laid down that, in general, no test need be made in such cases unless inspection suggests the special desirability of testing. Full tests are not normally required on reconnection of installations which have remained unused for three months or less, but careful visual inspection is carried out of all installations about to be reconnected. New installations and those which have been out of service for more than three months are to be subjected to a minimum test comprising the tests detailed in The Institution's Wiring Regulations (Nos. 1101 to 1106, Twelfth Edition).

A specimen schedule has been issued of defects commonly encountered, codified to make easy the installation inspector's reference to what he may find in installations. A Standard Test Schedule has also proved to be useful in ensuring that all prescribed tests are made and the results recorded.

Standard maintenance provisions for public lighting installations have also been adopted. Although this is not part of its statutory obligations, the Board undertakes the maintenance, under agreement with the respective lighting authorities, of nearly 100 000 public lighting points. Many large-scale conversion schemes for existing gas lighting are in abeyance only on account of restrictions on the local authorities over capital expenditure.

## (5) ADMINISTRATION

### (5.1) Engineering

Whilst the London Board, at Vesting Day, in common with other Boards, adopted the well-known "three-tier" form of organization, and, as a general policy, favoured devolution of responsibility, it recognized that the Area, by reason of its compactness, would lend itself to the centralization of engineering matters more than would be economically practicable in larger Areas.

The Board accordingly arranged that Engineering Headquarters would assume direct responsibility for all work associated with the 22kV–66kV transmission systems and bulk supply points, whilst the Sub-Areas and Districts, under the guidance and control of Headquarters, would have responsibility for the distribution systems operating at 11kV and lower voltages. The principal functions of the Headquarters Engineering Department may be summarized as follows:

(*a*) Operation and maintenance of the main 22kV–66kV transmission systems and of the Board's extensive private telecommunication system.

(*b*) Planning, design and construction of new electrical works and buildings for reinforcements and extensions of the 22kV–66kV systems.

(*c*) Study and co-ordination of metering and protective equipment design and practice.

(*d*) Co-ordination of all engineering purchasing and of specifications, designs and methods.

(*e*) Co-operation with the London Division of the Central Authority in engineering plans of joint concern, and with the Authority and other Area Boards on engineering matters of common interest.

(*f*) Study of, and guidance upon, proposals from Sub-Areas for extensions and reinforcement of the 11kV and lower-voltage systems.

(*g*) Provision and maintenance of a fleet of transport vehicles of various kinds for the work of all departments.

This Headquarters engineering work is shared by the four main functional branches of the department, namely: Operation and Maintenance; Design and Planning; Construction; and Meters and Testing. These branches have a technical staff numbering in all about 200. A similar functional arrangement is in operation in the Sub-Areas; the District Engineers, though located in the Districts, form part of their Sub-Area Operations and Maintenance Branch.

After several years' experience of this form of Sub-Area and District organization, it was realized that the functional organization, under which the duties and outlook of a large number of engineers are concerned mainly with a particular aspect, is not one that tends to produce men with wide distribution experience, or enables those with ability to fit themselves for management.

This view formed part of wider considerations relating to economic administration of the Area, and in April, 1953, advantage was taken of an opportunity which presented itself to disband one Sub-Area and its five Districts and replace them by two Districts, each with its own manager responsible directly to Headquarters. Among the aims of this reorganization was that of eliminating functional working as far as possible, so that the engineers in such new Districts might have the opportunity of becoming distribution engineers in the widest sense and of fitting themselves for higher responsibility. It is believed that the staff have welcomed the change, and the experiment is being watched with interest, not only in its economic aspects but also from the point of view of the impact on consumer relationships of greater local autonomy.

### (5.2) Commercial

Except in matters of policy, the commercial aspects of the Board's work do not lend themselves to centralization so readily as does engineering, since it is important to have adequate commercial strength close to the consumers, i.e. at District level. The two-tier organization is thus well suited to commercial requirements.

The main commercial problem confronting the Board at Vesting Day was that of tariff standardization; the magnitude of the problem may be gauged from the fact that within such a comparatively small area, in which, however, some five million people are congregated, there were at Vesting Day no fewer than 270 different published rates for electricity supplies.

These rates varied between wide limits, and since complete standardization implies the adoption of an average of some kind, the difficulties inherent in such a procedure when consumers are living close together become at once apparent. The policy of the Board has therefore been to proceed by gradual steps towards

ultimate tariff standardization rather than by drastic changes. Successive tariff revisions have been planned and, so far as flat rates are concerned, have resulted in standard published rates throughout the Area of 5d. per unit for lighting and 1¾d. for heating and power. Two-part rates are not yet fully standardized, but vary in their bases and monetary values. Considerable data have been accumulated for their ultimate unification, but in the meantime, on successive tariff revisions, steps have been taken so to adjust the monetary values in the different forms of tariff as to bring about, as closely as is practicable, equivalent charges for equivalent service.

It is not intended, in a survey paper, to discuss forms of tariffs or their monetary values in relation to capital investment and operating expenditure. It may be mentioned, however, that by the adoption of realistic tariff policies, based on the principle that the activity should be run on sound business lines and the Area be self-supporting, a surplus, modest by normal commercial standards, but nevertheless a surplus, has been achieved by the London Board on each year's working. Despite mounting costs in recent years, administrative and technical economies have been significant in enabling retail tariffs to be held down to rates which, in relation to pre-war ones, show modest increases compared with the increases in cost of consumer goods and other services to the London public.

## (6) STATISTICS (LONDON ELECTRICITY BOARD)

The compilation and presentation of statistics is an art, or artifice, which, interpreted with proper reserve, can add much to knowledge.

This Section is intentionally presented as statements of fact, with a minimum of comment.

### (6.1) Maximum Demand and Units Sold

Fig. 7 shows the aggregate maximum demands, actual and estimated, of public electricity in the Area of the London Board, for the period from 1926 to 1970 and the units sold during the period from 1935–36 to 1952–53.*

### (6.2) Length of Cables Installed

Fig. 8 shows the length, in circuit miles, of cables installed in the Area, giving the cumulative totals at and since Vesting Day.

### (6.3) Capital Expenditure

Fig. 9 shows the capital expenditure and its apportionment between transmission, distribution and other items.

### (6.4) Fault Analysis

Some 24% of all the faults which have occurred since Vesting Day were due to external agencies over which the Board has little or no control, e.g. mechanical damage, fire, flood, vermin and incidents on consumers' installations. A relatively large number of faults occur on medium-voltage cables in certain Districts, owing to the continuance in service of old distribution networks which would have been replaced but for the restrictions on capital expenditure.

Regarding the higher-voltage systems, at 66kV faults have occurred at the rate of about one per annum per 100 circuit miles. On the 33kV and 22kV cable systems, taken together, the

* The early part of the winter of 1953–54 proved exceptionally free from frost, but in late January and early February prolonged low temperatures were experienced. The temperature in London did not rise above freezing, day or night, for some ten days. This resulted in a simultaneous maximum demand on the 3rd February of 1 745 MW, some 200 MW in excess of that experienced during the previous winter. The total daily energy supplied reached a maximum of nearly 29 × $10^6$ kWh, this being some 20% in excess of the maximum of the previous year. Tribute is paid to the London Division of the Central Authority, whose efforts in making generating plant available enabled this load to be carried without the necessity for disconnection of any supplies.

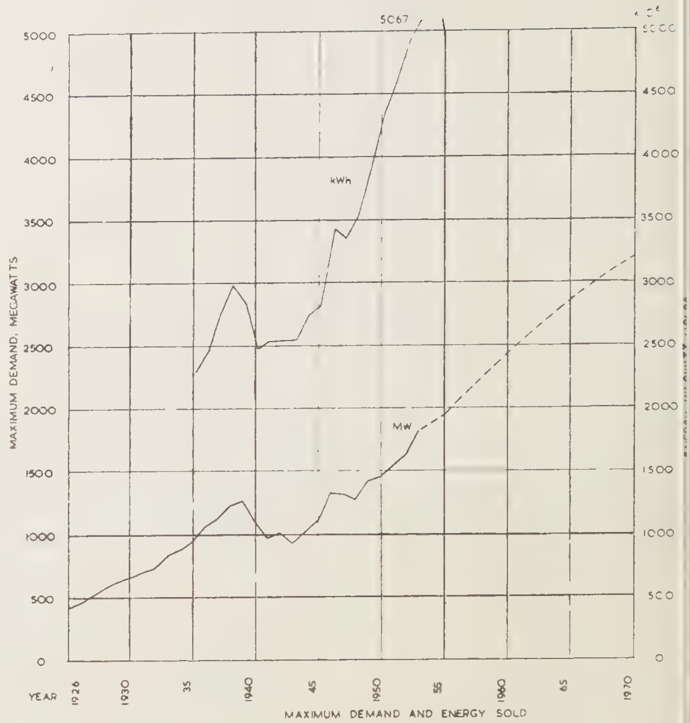


Fig. 7.—Maximum demand and energy sold.

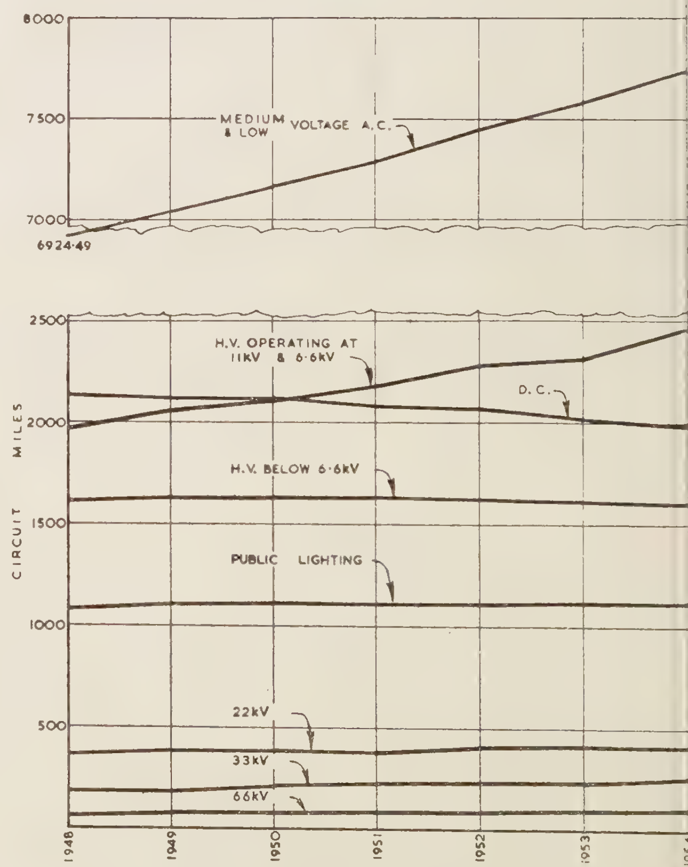


Fig. 8.—Length of cables installed.

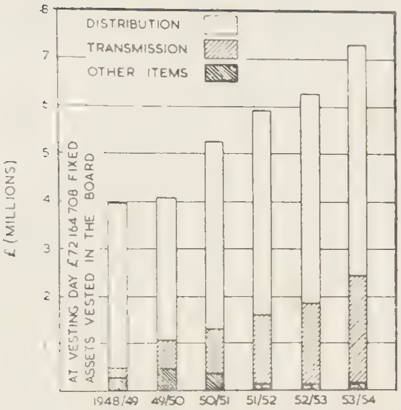


Fig. 9.—Annual capital expenditure, 1948–54.

equivalent assessment is 1·6 faults per annum per 100 circuit miles. The majority of faults have been in joints.

The 11kV and 6·6kV cable systems are subject to much mechanical damage by reason of their extent and of the difficulties encountered in parts of London in laying them in an adequately protected manner. The assessment of faults on these systems is, however, only 0·5 fault per annum per 100 circuit miles due to mechanical damage and a similar rate due to failures in joints and terminations.

### (6.5) Electrical Efficiency

A yardstick by which the administration can assess the effect of the skill and attention devoted to the technical needs of the enterprise is the trend of the relationship between the units sold to consumers and the units purchased. The figures available have a limitation in that all meters cannot be read at the precise end of the year, but in the London Area the year-by-year comparison has revealed electrical efficiencies of:

| | | | |
|---|---|---|---|
| 1948–49 .. | 86·65% | 1951–52 .. | 88·05% |
| 1949–50 .. | 87·52% | 1952–53 .. | 88·10% |
| 1950–51 .. | 86·55% | 1953–54 .. | 88·49% |

The reduced efficiency in the third year is reflected in the national figures published in the Ridley Report.[6] It may, to some extent, be attributed to the losses in the older, heavily loaded systems during the prolonged period of cold weather in that winter.

Substantial savings accrue from the upward trend in the electrical efficiency of the Area, each 1% improvement representing, to-day, nearly £150 000 per annum.

## (7) CONCLUSIONS

Six years' experience of planning and operating the distribution of electricity in the London Area as one enterprise has confirmed many previously entertained opinions and shown the fallacies of some others.

As a result of the unification brought about by the Electricity Act, 1947, it has been possible to effect considerable savings, which offset in no small measure the general increases year by year in the cost of labour and materials.

The average rate of growth of maximum demand in the Area is about 100MW per annum, and when war-time arrears of transmission construction work have been overtaken it should be possible, apart from the replacement of non-standard equipment, to settle down to a consistent rate of reinforcement equivalent to about two or three main supply points each year. In the past five years it has been necessary to build at double this rate.

In an Area so overwhelmingly built-up it will, however, become increasingly difficult to obtain suitable sites in the vicinity of the load demand, and compulsory powers of purchase may have to be invoked more frequently than has been found necessary in the past.

A close study of such parameters as are available refutes any suggestion that demand saturation is in sight or that, in the absence of unforeseen national circumstances, the rates of growth of demand and energy sold will slacken for many years to come. Fig. 7 shows the demands and energy sold in the Area over a reasonably long period, and extrapolation suggests a maximum demand around 1970 of about 3 250MW.

One is fortified in accepting this conclusion by the knowledge that the annual consumption of electrical energy by the Board's consumers now, notwithstanding the effects of a major war, is as great as that given in the Electricity Commissioners' returns for the whole of Great Britain in the year which saw the creation of the Central Electricity Board.

## (8) ACKNOWLEDGMENTS

The author acknowledges, with thanks, his indebtedness to the Chief Officers of the London Electricity Board and to the senior staff of the Engineering Department for assistance in the preparation of material for the paper, and to Mr. E. H. Jesty for help in its compilation.

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# DISCUSSION BEFORE THE SUPPLY SECTION, 18TH MAY, 1955

**Mr. Forbes Jackson:** Whatever views may have been held about the rights or wrongs, merits or demerits, of nationalization, there can be no doubt that London was a special case and badly in need of some kind of reorganization. Everybody knew that the London arrangement was wrong, and as the author has said, for a long time the London County Council received various reports on the subject which were either shelved or rejected by Parliament.

A report drawn up in 1914 by Charles Merz, who had been asked by the L.C.C. to report on the position of London's electricity supply, stated, in very polite language, that the situation was terrible, and added "that the fundamental cause of the existing state of affairs in London is to be traced to the action of Parliament." The final recommendations state that "the most satisfactory and economical method of achieving the result is

the establishment of a new undertaking with such power as will enable it to bring about the amalgamation of all the various undertakings." Incidentally, in the report, one of the main difficulties that the present author has described is clearly foreshadowed. It is stated that, unless something were done, we would find the system growing with the flow of power in the wrong direction and with the interconnecting voltages incorrect. At the time of the report the maximum demand in London was about one-tenth or one-fifteenth of what it is at present, and the total capital expenditure, including power stations, was between £20 000 000 and £30 000 000.

The supply industry is accustomed to working under administrative and statutory regulations, and I do not suppose that the new organization makes very much difference. However, I feel that, in the final result, the industry will have more freedom than ever before. This may sound paradoxical; the industry has been brought under control, and yet it will have more freedom to do things than before.

I think that the Metropolitan Board of Works initiated the first public lighting installation, in 1878, on the Thames Embankment. This precedes the one mentioned by the author by three years. It is true that it was subsequently dismantled and the Board reverted to gas lighting, but they did install electric lighting in 1878.

As the author has stated, the L.C.C. was very interested in the whole question of supply, and at one time it seemed possible that they would do something about it themselves. However, I think that it is as well they did not. The business of supplying electricity in London is so vast that it must form the full-time occupation of a body with no other distractions or duties.

From Fig. 1, which shows the London area before Vesting Day, it is clear that there were so many undertakers that some confusion and overlapping were inevitable. Nevertheless, if you knew your way about the jungle it was good fun and not altogether without profit to the consumer. For example, having negotiated a special tariff with one undertaker one could go to the next one and say "I have got this from so-and-so." In the end I got all the undertakers to agree to a common policy on housing supplies, and I thought this was a triumph. On another occasion the borough electrical engineer and the borough treasurer were at loggerheads as to the price at which I should get a supply for a rather important load, and I was invited to attend a meeting of the borough council and put the case direct. I cannot imagine a consumer being invited to do that now.

I am interested in the number of minor substations, i.e. 7 128. The 500 kVA transformer as a standard is a very sound idea, and naturally the Board is anxious to house that transformer at minimum expense and to pay only a nominal rent. If one has a building which requires only 100 kVA of load, it is a little difficult to be persuaded that one ought to find room for a 500 kVA transformer, because of the feeling that one is subsidizing some other consumer.

I know all the difficulties involved in getting tariffs standardized, but I also know that the difference between them is more apparent than real, i.e. although the form of the tariff differs the money which has to be paid for a certain amount of energy is about the same. However, that is really a good reason for making the change. The public did expect quite quickly to get uniformity of tariff structure, and I do not think that the Board has done enough about it.

**Mr. J. W. Leach:** The modern low-voltage network is more or less standard, but the methods of injection from the higher-voltage systems vary a good deal, and a greater dissemination of knowledge and experience in this would help us to obtain the highest economic efficiency. This is a paper dealing with London, and it is common to hear people say "That is all very well for London, but . . ." London is not exceptional, and what applies in the centre of London is not very different from what applies in the centre of any large city. Experience in London can be of benefit to other large cities and conversely, experience in other large cities elsewhere in the country can be of great interest and help to London. This is the second paper which we have had on London distribution, and I would plead for more knowledge of what is going on in other places.

I note that the main substation capacity averages 30 MW, and it would appear that the standard design of 50 MW is satisfactory. In the centre of London, where the sites for the installation of main substations and e.h.v. cables are congested and expensive, it may be necessary, however, to go to higher-capacity units for the substations. I see no difficulty in this; it is quite possible to increase the reactance of the transformers and at the same time to extend the range of voltage control to prevent any excessive rise in the short-circuit capacity of the l.v. systems. In other parts of London and elsewhere in the country I see no reason why single-transformer injection should not be applied as in the l.v. Grid system. I should like to see it tried, because I believe that it would be advantageous in saving cost.

I note that the l.v.-system transformer utilization or plant load factor is approximately 50%. That is a great accomplishment and approaches the design figure of 75%. That must have led and be leading to greater economy. It can be applied, of course, only where there is an interconnected network, i.e. the so-called solid network.

In Section 3.5 reference is made to a very interesting trial of what was once called the American network protector arrangement, and it will be watched with very great interest. It should be tried, and I hope that the results will soon be available. The two feeders through the same district will increase the length of cable as compared with previous systems, and that will increase the cost, and also the liability to faults, because of the greater length. On the other hand, the increase in cost may be offset by savings in switchgear; apparently the claim for economy is mostly based on lower costs by outdoor construction—a factor which, however, can be applied to any other form of equipment. It will be very interesting to see the results. I doubt whether there will be much difference in cost, but the system should be tried out, because it might be more practicable for some types of installation. In the same Section, I hardly think that the author intended us to understand that these interconnected systems, the so-called solid systems, have a lower limit of 100 MW. I believe that in Berlin in the early days they started with 3 MW, and in the old Central London system 5–10 MW was accomplished successfully.

In Section 5.1 the author refers to the intention to try out an interesting new arrangement. Of all the nationalization projects, that for electricity has been the most successful and trouble-free, and I am certain that the administration layout prescribed at the time, embodying Sub-Area Managers, together with the inherent loyalty of the engineers to their job, has really ensured this success. It is stated that the change which is being tried out is intended to give wider experience to engineers. I believe that it will cut both ways. I think the plan for Sub-Areas was never intended to prevent a man getting a full experience; in fact, there were to be transfers between different sections so that he should. If there are any organizations which prevent men from getting wide experience they should be altered. The closer we get to the top-level positions the more difficult it is to find the right men, but if we dispense with Sub-Area Managers and go straight from the Area Executive to the District Manager there will be a gap. For Area Executive positions we could get from the ranks of Sub-Area Managers men more mature and with a wider experience than at District level. However, this should be

tried, and it is very interesting to see that it is going to be tried. Nationalization was an enormous undertaking, and seven years is not a very long time in which to disentangle the muddle which existed in many places such as London. The Sub-Area manager system has served so well that great care should be taken before it is radically modified at this comparatively early stage.

Electricity should be cheaper. There is no such thing as saturation of load. In addition to the methods mentioned in the paper there are others to which I have referred before.* One is peak-load relief by gas turbines. In London these could be installed on the sites of old generating stations. I think that every Board should have the right to install generating plant if it can justify each particular installation. It would give a Board a very much better chance to negotiate and to keep its own costs down. Apart from interconnected networks there should be supervisory automatic control of load to get a better utilization of plant, because there are new kinds of load coming along and what is now called off-peak load may turn out to be the peak load if one is not prescient; with supervisory control at the bulk supply points, one can so dispose of the load during the day and at different times of the year as to cut the peak loads.

There is another way in which we can decrease costs. Cables can give perfectly satisfactory service for 50 years. In Section 2.4 the author mentions 11 kV cables laid in 1901 and 22 kV cables laid in 1905. That means 50 years of life in a very rough service. In some cases the joints were a little weak, but that was to be expected, because in 50 years we have learnt a great deal and made many improvements; I think it is perfectly safe to say that modern cable has a life of 50 years, and probably more. If the short-circuit capacities are kept right and the systems are planned so that they remain constant, switchgear can have a life of at least 50 and possibly even 100 years. Transformers should have a life of 50 years; oil conditions are better and loading conditions are more uniform than they used to be. Therefore I would now assign a life of 50 years to all this distribution plant, and that would reduce interest and sinking-fund charges.

**Mr. B. Donkin:** It is apparent that the London Electricity Board and their predecessors have been pioneers in the use of the gas-pressure cable. They have tested a number of different types, and I imagine that by now the author has a good idea which of those different types has in practice worked the best and which he would use on any further extensions. It is of interest to know also that one of the newer types of gas-pressure cable has an aluminium sheath. I believe that the main advantage of an aluminium sheath is that it is not necessary to reinforce it in the way that lead sheaths have to be reinforced, and I should therefore be interested to have any information on the author's experience with these newer types of gas-filled cable. Do the conditions of laying in the London area make gas-leak location difficult? I can imagine that a gas leak might be most difficult to locate and repair. It is possible, of course, that they are very rare, and therefore that the problem does not really arise.

One question arises from the excellent film on cable spiking which the author showed. How is the cable identified, particularly when it may be necessary to rely on incomplete records? There are, of course, various systems of identifying cables, such as those in which an a.f. note is transmitted down the cable and a pick-up is used, but it would be interesting to know how, in a very complex system such as that in London, the identification is carried out.

Since the London Electricity Board receives its power at various sources from the Central Authority, it would be interesting to know what arrangements, if any, are made for the control of power flow over the system and over the various interconnectors. Do they use tap changing with quadrature transformers in order to be able to control the power flow, and what provision is made for ensuring the maintenance of the correct voltage at the consumer's terminals? In other words, where is the voltage control? Is it on the distribution transformers or at some intermediate point on the transmission? Does the very large electrical capacitance on the London cable system give rise to any difficulties of voltage control during light loads at night or at week-ends?

The development of the distribution network using network protectors is novel, and it would be interesting to know what fault current is available on the consumer's terminals and whether it is found that consumers' protective devices, i.e. fuses, are capable of rupturing the fault current which is available on occasion. On an interconnected system of this sort I imagine that the fault current can be very considerable.

It is remarkable that about 10% of the consumers are still on direct-current systems. Perhaps the actual percentage of load is not as high as 10%. I do not know why they have not been converted, but I imagine that it may be due to the longevity of d.c. plant and the unwillingness of the Authority to incur the expense involved.

In many of the buildings supplied by the L.E.B. there are requirements for alternative sources of supply. It would be interesting to know how, with this interconnected network, those alternative sources of supply are provided.

This new development of network protectors is used extensively in the United States on a somewhat different system; the currents there are larger owing to the lower voltage. It would be interesting to know whether experience in this country indicates that when faults occur on a network they do, in fact, burn themselves clear and whether the network protectors protect not so much the network but the h.v. feeders and the distribution transformers from feedback if there is failure on the h.v. side.

**Mr. L. H. Welch:** It is well known that London had a great deal of d.c. distribution in the 1920's, and about 1925, Mr. P. L. Riviere, who was then the Chief Engineer of the Westminster Electric Supply Company, was faced with a very big decision. Should he continue with direct current or convert to alternating current? He made the decision to convert to alternating current and indeed to a simplified form with no duplicated h.v. supplies. This became the first solid system to be laid in London. It is not generally recognized that in London a solid l.v. system has existed for 25 years, and carries a considerable load. Considerable experience has been gained with that system which was described in detail by Mr. Leach many years ago.

Mr. Forbes Jackson has already referred to the consumers' point of view, but he has not mentioned that if he wants 100 kW to be supplied he still has to have a switch, a cable and a building, and the fact that he has a 500 kW transformer does not make much difference. Furthermore, he is provided with a standby from the l.v. network, and thus avoids having to have two transformers, and in the long run he gets greater reliability and a cheaper service.

**Mr. H. V. Pugh:** In Section 2.3 the author refers to the operation of 28 power stations of an aggregate capacity exceeding 3 250 MW. I am glad he says "exceeding," because the figure now is nearly 4 000 MW. In the last three complete years the London Division have installed 1 000 MW of new plant and have kept abreast of the demands not only of London but of the surrounding districts—because only 55% of the energy generated in the London stations is actually used by the London Board and 45% by the railways and other Boards.

It would be ungracious to complain about the tribute which the author makes in the footnote to Section 6.1. Although

* LEACH, J. W.: "Supply Section: Chairman's Address," *Proceedings I.E.E.*, February, 1950 (97, Part II, p. 9).

relegated to a footnote, it is very encouraging to see it stated in print. I do not think it has been generally recognized what great efforts have been made in maintaining the plant and having as high an availability as possible during the winter. During the last spell of cold weather many of the power stations had all the plant available—in other words, 100% availability. It is not always easy to do that with plant some of which is 50 years old. In dealing with system peaks the load factor of some of this old plant may be about 5%, and at such low load factors there is no reason why it should not continue to operate for ever, provided, of course, that it is safe to do so. Three years ago some of the old stations, like that at Bankside, produced over 100 million kWh in a year. Since then the output has dropped considerably; in the last full year Bankside generated about 30 million kWh. That seems to be the pattern for the older stations. If they are kept in commission they will still do very good work by meeting a demand in megawatts rather than producing megawatt-hours.

The efficiency of the London power stations, owing to the smaller output of the old stations, has, of course, increased, because we have relied for maximum output on the more modern and efficient plant. I am pleased to say that, in parallel with the increase in efficiency of distribution, the thermal efficiency has improved to 25%.

**Mr. R. R. H. Taylor:** As Mr. Pugh has said, some 40% of the power generated in the London power stations is used outside the L.E.B. area. A large proportion is used to the west of London, where there is a large area, quite heavily loaded, with few adequate generating-station sites. We must therefore expect that the transmission in London will be from the Thames Estuary towards the west.

The Central Authority and the Area Boards work closely together in planning their main transmission and distribution systems with the objective of designing and installing supply arrangements which are the most economic overall, irrespective of the way in which the costs fall on the Authority or the Area Boards. One good example of such joint planning with the London Electricity Board is the Barking–Ilford 132 kV connection, whereby a new point of supply has been established at Ilford instead of more expensive reinforcement at 33 kV from the existing point of supply at Barking. The author has mentioned the supply to Bengeworth Road from Deptford. The nearest power station to Bengeworth Road is Battersea, but the Area Board took the supply from Deptford in order to maintain the east–west flow. Had they taken the supply from Battersea the Authority would have had to provide a transmission reinforcement from Deptford to Battersea. Another example of joint planning is the complete integration of the L.E.B. 66 kV system and the Central Authority 66 kV system which is at present in progress at Lodge Road.

If we consider the system which the Central Authority took over at Vesting Day, we find that the distribution of municipal undertakings and company undertakings north and south of the river led to the C.E.B. having an extensive system north of the river but very little to the south. As a result the Area Board have many more points of supply in the north than in the south. The major reinforcements of the Central Authority system have so far taken place in the north, with new transmission from Brunswick Wharf westwards to Islington and Holborn. Similar major reinforcements are envisaged for the south, but they have not yet been fully worked out. These developments will facilitate the general flow of load from the Thames Estuary westwards into the heart of London. There will also be transmission from the 275 kV Grid at points west of London, which are some miles out of the L.E.B. area, in order to pick up some of the load in the west which has no local generation to support it.

**Mr. H. D. Kenner:** Distribution costs are the largest item of capital expenditure, and it follows that a more economic system than that described by Mr. Leach in 1941 would partly release the brake on activity caused by present capital restrictions. I regard Section 3.5 as the most important part of the paper, but I do not think that the author has the best solution with the interleaved system described there. It appears to be economically and operationally unsound; economically, because although this method shows a small percentage saving on the total cost initially, cable must be laid prematurely to obtain the interleaving effect and transformers must be installed earlier than would otherwise be necessary, in order to provide back-up from the l.v. network during outages of the h.v. radials, so that additional interest and depreciation costs must be added. Further, a complete knowledge of the local load conditions to be met at the time of load saturation is difficult to forecast, and costly mistakes are probable in the lay-out of the system. Another item of expenditure often overlooked is the extra overtime rates of pay caused by work having to be performed during off-peak periods because of the inflexibility of the system, particularly during its construction.

The absence of sectionalizing facilities on the h.v. distributors, together with the purely radial layout, is operationally unsound. All transforming capacity is lost while a new transformer is connected or any other work carried out on the cable or its controlling circuit-breaker. A fault must be found and repaired before re-energizing, instead of being quickly isolated. A large amount of spare plant must therefore be available on the adjacent distributors in order to prevent the possibility of prolonged interruptions of supply.

However, the transformer unit alone, as described by the author, appears to be an excellent method of relieving the extremely high present-day costs of building and equipping a conventional transformer chamber. Also the network protector eliminates the need for an oil circuit-breaker, because power cannot feed back from the l.v. network into a h.v. cable fault, and modern transformers are reliable enough to allow the main substation circuit-breaker to clear a transformer fault. Also unnecessary are l.v. network fuse couplings, which, owing to the design of older networks, usually have to be used in such abundance as to interfere with the operation of the fault burning-off effect.

From the foregoing there comes to mind a synthesis of the two methods of h.v. distribution, i.e. interleaved and standard, combining the transforming economy of the one with the flexibility and cable economy of the other. This would entail the use of an outdoor transformer unit similar to that described by the author on the cable system described by Mr. Leach. Such a unit would require two isolators on the h.v. side instead of one. These would be in series on the h.v. distributor with the transformer solidly connected to the busbar between them, the busbar being inside the transformer tank. The only loss of flexibility under these conditions is that, when it is required to overhaul the unit, both isolators must be opened and therefore the distributor open-circuited. However, this will cause no difficulty with distributors laid in the form of ring mains. The necessity of bringing a new cable to the midpoint of an overloaded ring main can be dealt with by a simple underground solid-tee connection. It is suggested that all the l.v. network associated with one section of a main substation can be solidly connected with this method.

With regard to the standard size of 500 kVA for distribution transformers, the author states that loads of 200 MW/mile$^2$ are expected within 15 years in some areas. It is reasonable to believe that, as has already been pointed out, plant and cable being commissioned at the present time will last at least 50 to 60 years, and I would like to know whether the author has an

estimated figure of the load densities to be expected at a date near the end of the century, when this present-day equipment will still be serving a useful purpose. Bearing in mind our diminishing coal reserves and the consequent use of nuclear-powered electrical energy as the only substantial means in this country of providing artificial heat for industrial and domestic purposes, this figure must be considerable.

On the assumption of a load density of 200 MW/mile$^2$, which is surely a minimum estimate of that to be expected in many areas during the lifetime of present-day plant, and allowing 75% load on each 500 kVA transformer, 533 transformers and $5\frac{1}{2}$ main substations will be required per square mile. In view of these uneconomic figures it would appear expedient to immediately start installing transformers of 750 kVA rating as the best average value for the London area.

**Mr. W. Holttum:** The statement in Section 3.3 that paper-insulated lead-covered cables have proved to be among the most reliable of all items of electrical plant is very gratifying to the cable makers. I would like to ask whether the qualification "properly installed" refers to workmanship or to the method of installation adopted, i.e. buried or above ground on hooks, the latter method being regarded in certain quarters with, in my opinion, quite unwarranted misgiving. Where both alternatives are available, is there a definite policy as to which should be adopted? At the end of Section 6.4 reference is made to faults due to mechanical damage due to inadequate protection, and here again I would ask whether this refers particularly to one or other method of installation.

Regarding important new feeders, is it the practice to keep down the capitalized value of losses by putting in conductor sizes larger than those required to carry the current?

**Mr. L. H. Fuller:** It is very interesting to see the adoption of what I might call the outdoor style of substation, shown in Fig. 5. I assume that this has not been introduced before because of the preference for a circuit-breaker on the 11 kV side. If the objection is that a circuit-breaker is considered necessary, why cannot fuses be permitted, as these are quite satisfactory up to 500 kVA on 11 kV systems? The fuses can readily be left out, as shown in Fig. 5.

I wonder whether similar economies are made in the other districts which adopt the old-established practice of a very nice building, which may cost anything up to £400 and which, with the large number of substations in the London area, must represent a very considerable capital expenditure.

**Mr. E. H. Jesty** (*communicated*): The paper suffers from the inherent disadvantage of an impressionist picture: that of exciting our general interest but leaving unsatisfied our curiosity over details. I would have been interested in a more generous treatment of the supply of electricity to public lighting in the Area, which is an important part of the Board's activities.

In Section 4.2 it is stated that the Board maintains 100 000 lighting points—three times as many as a large provincial city like Liverpool or a capital city like Paris. But some of the municipalities carry out their own maintenance and the total number supplied must be even larger. Fig. 6 shows that nearly 2% of the total energy supplied is used in public lighting, and it is, perhaps, the only use of energy which has repercussions on 100% of the consumers. When public lighting in the Area has become all-electric it is possible that it may provide a total demand of some 30 MW, and if this coincides with the peak it will incur a demand charge approaching £150 000 at the present tariff.

In Section 4.2 the vexed question of the testing of consumers' installations by the supply authority is mentioned. In view of the recent High Court pronouncements it would be interesting to know whether the authority's responsibilities for the state of consumers' installations can be determined.

**Mr. R. H. Rawll** (*communicated*): There is an important omission in the historical section of this paper, to which some reference should be made. Although the author has pointed out that the Central Electricity Board, created by the Act of 1926, effected the interconnection of generation by means of the national Grid system, it should also be placed on record that some 12 years before this date, i.e. before the First World War, a scheme was prepared and arrangements were carried through by the neighbouring municipal electricity undertakings of Shoreditch, Hackney, Stepney and Poplar, each of which had its own generating station, whereby mutual aid in meeting the respective demands of the four undertakings could be made through inter-connector cables. It is thus interesting to observe that over 40 years ago there were, in fact, a number of engineers of vision, who not only recognized the necessity of thinking of London's electricity supply in terms beyond their own individual borough boundaries, but also, with the full support and co-operation of their Councils, took practical and initial steps in that direction, which, it should be emphasized, were of a purely voluntary character and not the result of compulsory legislation.

## THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

**Mr. D. B. Irving** (*in reply*): I am glad to note the interest displayed in the historical section of the paper, and thank Mr. Forbes Jackson for the further information he has given regarding the part played by the L.C.C., whose co-operation in the acquisition of transformer-chamber sites is greatly appreciated by the London Electricity Board.

I have reason to hope that it will not be long before the tariff standardization to which Mr. Forbes Jackson refers becomes a reality.

I support Mr. Leach in his plea for more knowledge of what is going on in other places, especially in the larger cities of the country. He is correct in assuming that I did not intend the figure of 100 MW per square-mile in Central London to be taken as the lower limit of load density for which network systems are suitable. They are economic in application at very much lower load densities.

One of the many advantages arising from the 2-tier organization is that young engineers can aim at entering the broader field of management at a much earlier age than they could possibly hope for in the present London organization. It is generally accepted that actually doing the job of management, with the associated responsibility, is a far better method of fitting a man for the higher positions than the method of short-period transfer between sections without real responsibility.

Mr. Leach suggests a scaling down of depreciation charges for distribution plant and cables as a means of cheapening electricity. At first glance his proposal appears attractive, even though, on paper, the saving in the Board's working costs per kilowatt-hour would only be measured in hundredths of a penny. We are, however, living in an age of invention and discovery and of great change-over from d.c. and other inefficient systems, their replacement being accompanied by substantial savings in the cost of losses and maintenance. If life periods are extended and plant or cables are replaced for reasons other than "wear and tear," before the end of the assumed life, a charge to revenue account arises in respect of both the replaced and the new equipment. The initial relief in revenue charge is thereby negatived.

In this era of intensive research, it would be a bold man who would say that equipment now being installed will not be replaced within the next fifty years.

The recent gas-pressure-cable installations to which Mr. Donkin refers are operating so satisfactorily that there is little or no experience available to enable me to answer his question as to whether the conditions of laying in the London area would make gas-leak location difficult. The type of cable selected for a particular installation would depend on the characteristics of the route and the service required of the cable.

The various electrical methods of identification known to us are used in London, cable spiking being the safeguard adopted if any shadow of doubt remains.

The Board have not so far found it necessary to install quadrature transformers to control power flow, since their system is, for the most part, a transmission system. Tap changing for voltage control is used at the Central Authority supply points and at the Board's main substations where the incoming voltage is stepped down to the distribution voltage of 11 or 6·6 kV. No on-load tap changing is employed on the 500 kVA distribution transformers.

No difficulties in voltage control have arisen at periods of light load, but on what is now the Central Electricity Authority's system, the former Central Electricity Board did install a few shunt reactors to counteract the capacitance on the cable system. The maximum short-circuit power on the low-voltage solid network has been estimated at 25 MVA, as mentioned in Section 3.2 of the paper.

The rate of change-over from direct-current systems has been limited by the restrictions on capital investment imposed by the Government on the industry, but despite this the number of consumers in London receiving d.c. supplies has been reduced since Vesting day from some 230 000 to about 148 000.

The network protectors on the system now being tried out, do, in fact, as the name implies, protect a healthy network against unhealthy h.v. feeders or distribution transformers.

Mr. Welch's comment that Mr. Riviere, when Chief Engineer of the Westminster Electric Supply Company, laid down the first a.c. solid network in London 25 years ago, is of considerable interest. Its continued development endorses the wisdom of the decision made at that time.

One of the questions raised by Mr. Forbes Jackson is answered by Mr. Welch.

I am glad to hear from Mr. Pugh of the generation developments which have taken place since the paper was written, and I do hope that a survey paper relating to generation in London will be forthcoming.

With Mr. Pugh I am sorry to see my tribute to the staff of the London Division relegated to a footnote. In the original text I had incorporated it in its proper place—the body of the paper.

I thank Mr. Taylor for his comments on the joint work of the Central Authority and the London Board in planning their systems, a work in which he himself has taken a prominent part. Only by cordial co-operation of this kind can the most economic overall plans be made.

Mr. Kenner suggests a combination of the network protector and the West End system as being better than either. The West End system has, however, adequately proved its reliability under London conditions, and the network system has proved itself abroad. The latter is therefore being given a trial to assess the merits of its application in London. Mr. Kenner's criticism that, in the network system, cable must be laid prematurely is rather in conflict with his subsequent suggestion that 750 kVA distribution transformers should now be installed rather than 500 kVA ones to meet the more distant load growth.

Referring to Mr. Holttum's comment, the term "properly installed" refers both to workmanship and the method of installation adopted. Practically the whole of the cable in London is laid underground.

When installing important new feeders many factors, other than the capitalized value of losses, are taken into account, and conductor sizes are not made greater for the specific purpose of reducing losses.

The use or otherwise of the outdoor style of substation mentioned by Mr. Fuller is not at the option of the Board in a built-up area such as London. The majority of transformer chambers are accommodated in buildings owned by consumers.

I share Mr. Jesty's feelings, but in preparing a survey paper of this nature the problem becomes one of deciding what must be omitted. I hope, however, that this broad survey will be supplemented by papers dealing with some of the more particular aspects of electricity supply in London by members of the Board's staff whose special interests they are.

I am indebted to Mr. Rawll for drawing attention to the arrangements made by some of the London municipal electricity undertakings in 1914 to provide mutual assistance.

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Paper No. 1894 S
Dec. 1955

# THE REPRESENTATION OF IMPEDANCES ON THE RESISTANCE NETWORK ANALYSER

By J. H. FIELD, Member.

(*The paper was first received 7th December*, 1954, *and in revised form* 28*th April*, 1955.)


## SUMMARY

Owing to the high cost of a.c. network analysers for power-system studies, attempts are often made to solve problems involving resistance, reactance and power factor on d.c. analysers equipped only with resistors. It is then necessary either to ignore phase displacements and accept errors in the solution or to adopt artifices to obtain greater accuracy—and therefore to introduce increased complexity.

A method has been developed whereby a conventional network analyser equipped only with resistors is energized from a 2-phase a.c. supply and phase displacements due to reactances are obtained by injecting voltages which are constant in direction.

The method is applicable to either load flow or fault studies if transient effects are absent.

The additional equipment required is inexpensive when an orthodox resistance analyser is available, and the accuracy of the solution is high provided that any rotating plant involved is operating in the steady state. The method is not suitable for the study of stability problems or transient effects.


## LIST OF PRINCIPAL SYMBOLS

$L_1, L_2$ = Loads supplied from a power system.
$V_S$ = Sending-end or generator voltage (reference vector).
$V_{AB}$ = Voltage across branch AB.
$V_A, V_B$ = Receiving-end or load voltages.
$V_1, V_2$ = Displacement voltages.
$V_q$ = Voltage to be injected into branch for phase shifting.
AB = Typical line branch of a power system.
$R, X$ = Resistance and reactance of a branch of a system.
$\phi$ = Arc tan $X/R$.
$\theta$ = Angle of inclination of voltage across branch to voltage reference vector.
$\alpha$ = Angular error in the direction of a vector due to imperfect apparatus.
$R' = R + X \tan(\phi - \theta)$
= Adjusted value of resistance to be set on analyser.
P, Q = Two a.c. supplies with a phase displacement of one right angle.
$I$ = Current in branch of power system.

## (1) INTRODUCTION

It is generally recognized that mechanical assistance is essential for the engineer who is called upon to forecast the performance of a power system even in the steady state. This assistance falls into three classes—the alternating-current analyser, the mathematical computer and the direct-current analyser. The first is an expensive machine, whereas the second requires a trained operator and is therefore seldom suitable for the power engineer. Because of the low cost of the equipment necessary for the third method it is often employed to solve two-dimensional problems (namely those involving complex quantities) although the machine is essentially one-dimensional in scope. For purposes of clarity, this d.c. machine will be referred to as a resistance analyser.

The paper describes a method whereby a conventional resistance analyser can be extended cheaply to solve two-dimensional load-flow or fault problems involving resistance and reactance, provided that any rotating plant involved is operating in the steady state. The method is not suitable for the study of stability problems or transient effects.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
Mr. Field is with the South of Scotland Electricity Board.

## (2) THE PROBLEM

In the study of a steady-state performance of a power system, two problems require solution, namely fault levels, including the disposition of fault currents within the system, and load sharing by the branches of the system.

The general principles of solution are identical for the two problems, but the dimensional limitations of the resistance analyser have resulted in the adoption of different techniques for their solution.

### (2.1) Fault-Level Studies

Because of the dimensional limitation of the analyser, a fault-level problem is generally made one-dimensional, the analyser being set to represent reactances only, resistances being ignored completely. On systems designed to operate at, for example, 132 kV or above, the ratio of reactance to resistance for the branches of the system is generally high, and the errors introduced by ignoring resistance values are negligible. In recent years, however, resistance analysers have come into increasing use on systems at lower voltages where, in some cases, the reactance of a branch may be less than its resistance and the ratios of reactance to resistance may vary considerably in different branches.

The errors caused by neglecting resistance values then become appreciable and computed fault levels are much too high. One artifice used to overcome this disadvantage is to adjust the analyser settings to represent impedances instead of reactances. The analyser can only deal with these as scalar quantities and the computed fault levels are inaccurate except in the rare cases where the ratio of reactance to resistance is constant throughout the system. In other cases it is often assumed that the computed fault-level errs on the side of safety, although this view is not invariably correct.

### (2.2) Load Flows

In many load-flow problems the errors resulting from the one-dimensional limitation of the resistance analyser are of such magnitude that direct methods of solution are useless. A number of indirect methods have been devised whereby improved accuracy can be obtained. They suffer from the common disadvantage of being trial-and-error methods, but this does not necessarily impair their accuracy, nor does it involve a serious waste of time in the hands of a practised operator.

#### (2.2.1) Hahn Method.

Hahn[2] developed a method in which the power system is represented by two networks on a resistance analyser, neither network having any direct counterpart on the power system. After adjustment of the analyser for final readings, it is necessary to combine the flows in the two analyser circuits to compute the corresponding flow in the power-system circuit. In the manipulation of the values to be fed to the analyser, negative resistance

values frequently appear. Many of these can be eliminated at the outset by an artificial change in the position of the reference vector, and the corresponding correction can be applied during final tabulation of the results. On occasion this does not eliminate all the negative resistances. These can be dealt with in a different manner, although the analyser circuits become involved and troublesome.

(2.2.2) **Enns Method.**

This method[3,4] is based on the equations developed by Hahn, but it requires four independent circuits to be set up on the analyser. It is difficult to operate except on an analyser designed for the purpose, and the author has no operating experience of it.

(2.2.3) **London Division Method.**

This method, which is a modified form of that suggested by Hahn, was devised by the engineers of the London Division of the Central Electricity Authority for obtaining reactive and non-reactive load-flows in networks where, in general, the reactance of any branch is not less than twice its resistance. The voltage and phase angles which exist on the various busbars, together with the effect of tap changing on transformers can also be obtained direct from the analyser during the investigation.

Compared with the Hahn method it achieves simplification by assuming that the product of the reactive load and the resistance in each branch of the system, when investigating power flows, can be neglected. Also, owing to the approximate assumptions that are made, the risk of obtaining negative resistances is also very much less than with the Hahn method.

It is claimed that the errors introduced by the assumptions are virtually fixed in magnitude and, being small, are negligible on heavily loaded branches; hence the percentage error is small in critical circuits.

## (3) PROPOSED METHOD

Although it is customary for resistance analysers to be energized from d.c. supplies, it is no innovation to use a single-phase a.c. supply. The one-dimensional limitation is due not to the power supply but to the fact that generator, line and load units are all represented by resistors.

It appears to be illogical to attempt to solve two-dimensional problems with a machine which is inherently one-dimensional, not only in its branches (resistors) but also in its source of supply (direct current), and it is apparent that part of the dimensional constraint can readily be removed by energizing the analyser from an a.c. supply which is potentially two-dimensional. Unfortunately, to remove the constraint entirely it is necessary to provide high-quality reactances, and these and the medium- or high-frequency supplies often necessary for them result in the high cost of the orthodox a.c. analyser.

A need arose, therefore, to evolve a cheap method whereby the characteristics of reactances could be simulated without the use of physical reactances. For this purpose two sources of alternating current, referred to as P and Q and being 90° out of phase, are used in such a way that the shifts are not a function of the frequency of the power supply.

An elementary power system and its vector diagram are shown in Fig. 1 where a generator G supplies loads $L_1, L_2 \ldots$ by means of circuits GA, AB, BC. In the vector diagram for this system $V_S$ is the generator or sending-end voltage, $V_{AB}, V_{BC} \ldots$ are the voltage drops in the circuits and $V_A, V_B, V_C$ are the receiving-end voltages. The branch AB of the circuit, which may be taken as typical of all branches, can be represented exactly on a network analyser provided that the current entering and leaving it and the voltage between the terminals A and B correspond vectorially on the power system and on the analyser.

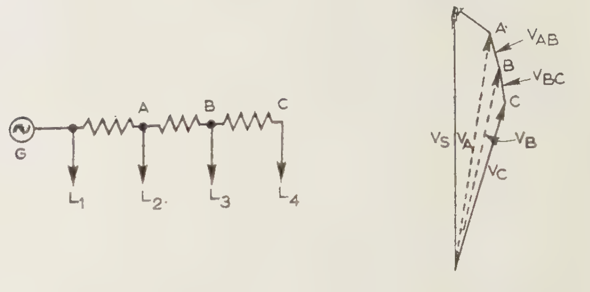


**Fig. 1.**—Vector voltage diagram for elementary power system.

If the system to be studied is set up on a resistance analyser energized from a source of alternating current having a known voltage $V_S$, and the voltage across and the current entering and leaving the branch AB (Fig. 2) are guessed, then by injecting into

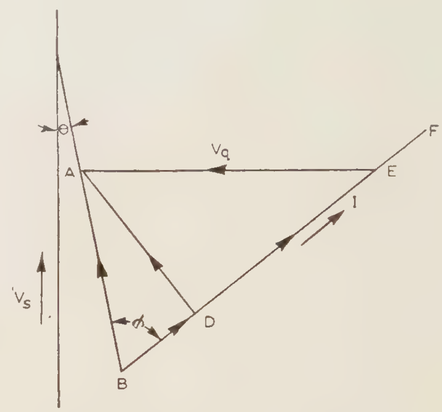


**Fig. 2.**—Resolution of voltage.

the branch AB a voltage $V_q = $ AE perpendicular to $V_S$ and suitably adjusting the resistance of the element representing AB it is possible to comply with the requirements as regards current and voltage at the terminals of AB.

The vector $V_S$ is the sending-end voltage, and is derived from the P source.

It can be proved that the value of voltage to be injected perpendicular to the P voltage is given by eqn. (1).

$$V_q = V_{AB}\frac{\sin\phi}{\cos(\phi - \theta)} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $\tan\phi =$ ratio of reactance to resistance for the branch.
and $\theta =$ inclination of $V_{AB}$ to $V_S$.

The voltage $V_q$ is obtained from the Q source by means of transformers.

It can also be proved that the requisite setting of the resistance representing the branch is given by eqn. (2).

$$R' = R \times X\tan(\phi - \theta) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $R =$ resistance of branch AB,
and $X =$ reactance of branch AB.

### (3.1) Application of Method

It is apparent that the correct values for $V_q$ and $R'$ for each branch can be calculated only after the problem is solved. The method is accordingly one of trial and error in which the vector values of the voltages such as $V_{AB}$ are guessed and corresponding voltages $V_q$ and resistances $R'$ are calculated and applied to the

analyser. Measurements are then taken on the analyser and used for the calculation of a new set of injection voltages and resistances. The process of measurement and re-calculation is repeated until the differences between successive sets of readings are insignificant.

(3.1.1) **Load and Generator Units.**

The method of using injected voltages and adjusted resistances could be employed to represent line, load or generator units. It is possible to simplify the procedure for loads by utilizing two a.c. supplies, with a relative phase displacement of 90°, one of which can be considered as the source of the active components of the load (P components) and the other as the source of reactive components (Q components). Thus each load is represented by two resistors, one connected to the neutral terminal of the P source and the other to the neutral terminal of the Q source. The two neutrals are not coincident.

becomes inconveniently large. The calculations for the settings are similar to those for the normal injection.

A simple method of representing transformer tap-changing has not yet been devised, but consideration is being given to the employment of auto-transformers for this purpose, and also for the simulation of quadrature buck and boost.

## (4) CONNECTIONS AND METERING

Unless they are constructed to represent a specific power system, resistance analysers generally consist of variable resistors capable of interconnection by means of plugs and sockets. Provided that the voltage to be injected is in series with the resistance required, the exact point of injection is of no significance. Thus a voltage injected into a connection between two adjacent elements is convenient in practice and fulfils the necessary condition (Fig. 3).

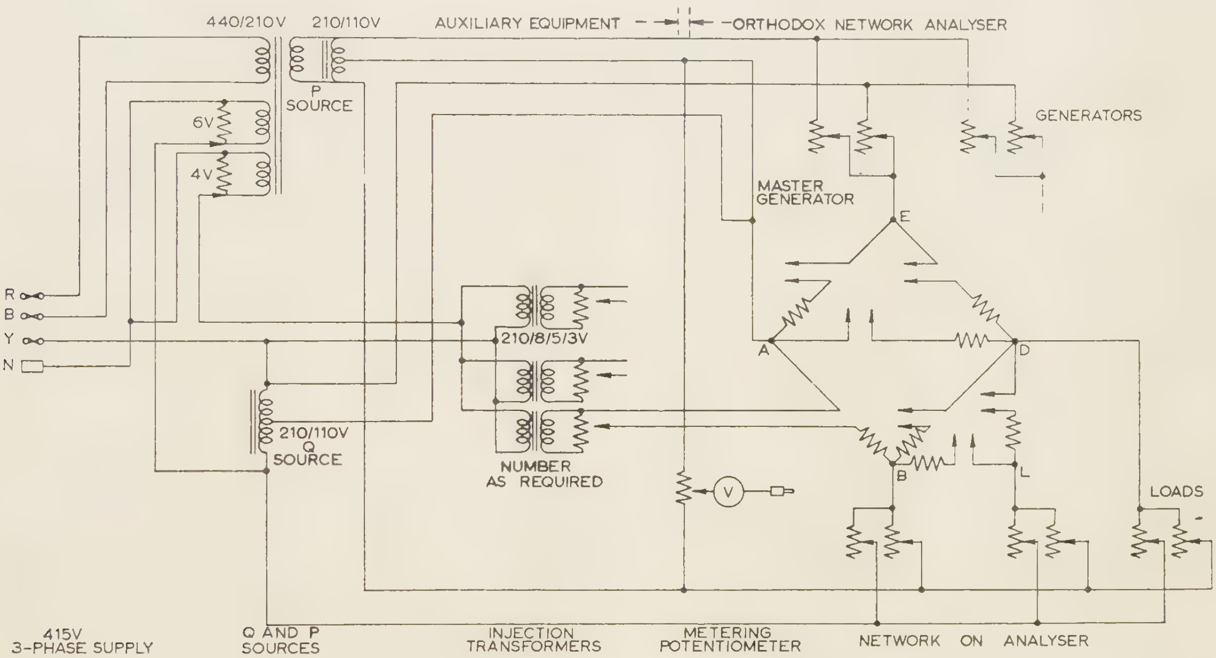


Fig. 3.—Extension of orthodox resistance analyser.

A generator may be considered as a negative load, and it is apparent that the same procedure may be used for the representation of generators. For these the two resistors are connected to the line, as distinct from the neutral, terminals of the P and Q sources. It is apparent, however, that it is only possible to adjust the output of all the generators less one, since one generator must supply the difference between the sum of all the loads less the output of all the other generators. This unique generator is called the master generator.

(3.1.2) **Capacitive Reactance, Negative Resistance and Transformers with Tap-Change Equipment.**

To represent a series capacitor, it is only necessary to reverse the connection of the injection transformer. To simulate a shunt capacitor a resistance is connected direct to the line terminal of the Q source.

Apparent negative resistances occur in some systems. These can be simulated by two injections, one from each source of supply. The same artifice is sometimes convenient for other purposes, as, for example, in a circuit where the current lags or leads by angles approaching a right angle and the injected voltage

### (4.1) Injection Transformers and Sources of Supply

The injection transformers themselves consist of the requisite number of small transformers, commercial bell transformers being suitable for the purpose. The primary terminals are connected between one phase and neutral of a 3-phase 415-volt supply, and the secondary voltage outputs are controlled by means of potentiometers. The same phase and neutral of the supply may be used as the Q source for the analyser. This supply is taken from an auto-transformer, the intermediate tapping of which becomes the Q master generator, and the phase and neutral connections are connected respectively to resistances representing the other Q generators and the Q loads.

The P source is derived from the other two phases of the 3-phase supply, and a standard radio power transformer (ratio approximately 440/240) is suitable for the purpose. A second auto-transformer is connected to the low-voltage terminals, the intermediate tapping of which becomes the P master generator, and the other P generators and loads are arranged as already described for the Q connections. The two master generators are connected together.

### (4.2) Imperfections in Equipment

Owing to imperfections in the transformers, neither the Q supply nor the outputs from the injection transformers may be perpendicular to the P supply. It is possible to correct errors arising from these causes by using auxiliary windings on the P transformer for quadrature buck or boost. Alternatively, if the angle between the output of an injection transformer and the P source is greater or less than 90° by an angle $\alpha$, proper correction for this may be made by substituting $(\phi - \theta \pm \alpha)$ for $(\phi - \theta)$ in the calculations for injected voltage and adjusted resistance.

The effect of the reactances of the injection transformers can be minimized in the choice of resistance value for the control potentiometers, and possibly by the insertion of a series capacitor in the h.v. connection.

### (4.3) Metering

The solution to a problem will be in terms of voltages, currents, watts and volt-amperes, and it would be ideal to use appropriate instruments to measure them. The instruments must not impose a significant burden on the circuits, and their cost would be high. It is possible, however, to reduce the number of essential instruments to one.

If the vector voltage across the terminals of a known impedance is known, the vector current in the element and the assotiated watts and volt-amperes can be calculated. Hence, the only essential measurements in an analysis are vector voltages, for which any voltmeter of low burden may be employed, a valve voltmeter being ideal.

To determine the direction of the voltage across the element AB, a potentiometer is connected across the terminals of the P supply to the analyser (Fig. 4). The moving contact of the potentio-

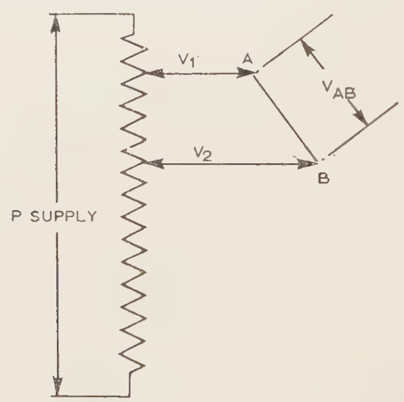


**Fig. 4.**—Measurement of voltage.

meter is then at a voltage which always lies on the reference vector. A voltmeter is connected to this contact of the potentiometer and to terminal A of the element on the analyser. The potentiometer is then adjusted until the voltmeter reading is a minimum, which occurs when the direction of the voltage $V_1$ is perpendicular to the reference vector, and this minimum value is therefore the displacement of terminal A from the reference vector. A second voltage reading $V_2$ for terminal B establishes the direction of the voltage across AB. The magnitude of the voltage across AB is measured direct. If available, an ammeter can be employed to set the resistors controlling the P and Q components of the loads to a first approximation, but this method is not essential.

## (5) OPERATING PROCEDURE

Since the method is one of trial and error, it is necessary to assume values for the voltage vectors for each element of the system to be studied. From these assumed values and the known values of the impedances, a calculation is made for each element of the resistance to be set on the analyser and the voltage to be injected into it. The resistance setting on the analyser must take into account the resistance of the injection generator when supplying the appropriate value of voltage. Voltage readings are then taken for each element, and a vector diagram of voltages is drawn. From this diagram are taken the data for a new series of calculations for resistances and injection voltages, and the process is repeated until the differences between successive vector diagrams is negligible.

## (6) CONCLUSION

The method suffers from the disadvantage, common to artifices of this nature, that it is a trial-and-error method. The labour involved in the successive computation is about the same as in Hahn's method, but the results of the analysis are more readily converted into the required form. It has the advantages of being negligible in cost when a conventional resistance analyser is available, and only requires the setting up of one network, as opposed to the two required by Hahn and the four by Enns. In consequence, an element on the analyser is an exact counterpart, so far as current and voltage are concerned, of the corresponding element of the power network. The accuracy of the first guess of values does not influence the accuracy of the final result, and convergency is reasonably rapid. The method has been applied to a number of problems, both textbook[1] and practical, and the results have been within the accuracy of slide-rule calculations with an appreciable saving of time.

It is considered that the method is entirely satisfactory for extending the use of an orthodox resistance analyser to the solution of a large number of two-dimensional power-system studies.

## (7) ACKNOWLEDGMENTS

The author wishes to express his thanks to Mr. T. R. Warren, Chief Engineer of the South East Scotland Electricity Board, for permission to publish the paper, to Mr. J. L. Egginton for advice and assistance in developing the method and preparing the paper, and to Reyrolle and Co. for the use of the problem illustrated in Fig. 5.

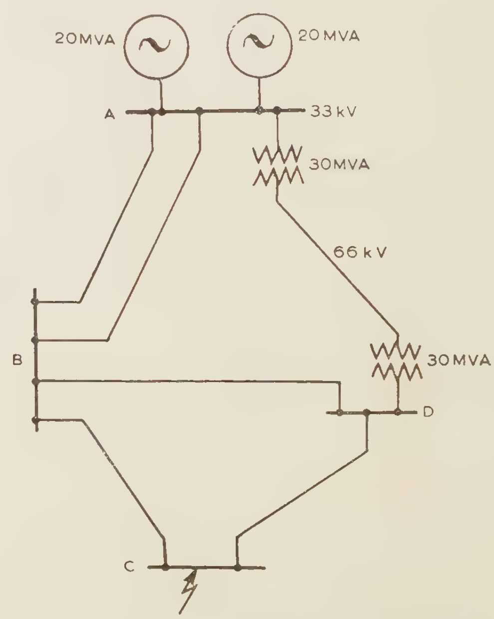


**Fig. 5.**—An interconnected network with fault at C.

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## (9) APPENDICES

### (9.1) Mathematical Computation

It is conventional (see Fig. 2) to represent a voltage AB due to the passage of a current $I$ through an impedance $Z$ by resolving it into two components $IR$ (= BD) and $IX$ (= AD).

This, however, is merely a special case of the general proposition that the sum of any two vector quantities is represented by the third side of a triangle in which the other two sides are represented by the two component vectors.

Thus it is equally true to say that the vector $AB\angle\theta$ is the sum of the two vectors $AE\angle 90^\circ$ and BE, the argument of BE being the same as that of BD, namely the angle of the current $I$.

$$\text{Now}\quad \angle BAD = 90 - \phi$$
$$\angle DAE = 90 - (90 - \phi) - \theta = \phi - \theta$$
$$AD = IX - IZ\sin\phi$$
$$\text{and}\quad BD = IR$$
$$\text{Therefore}\quad \frac{AD}{AE} = \cos(\phi - \theta)$$
$$\text{hence}\quad AE = IX\cos(\phi - \theta) = IZ\sin\phi\cos(\phi - \theta) \qquad (3)$$

and this is the value of the voltage $V_q$ to be injected.

Now BE is a voltage vector co-directional with $I$, and can therefore be simulated by the passage of a current through a resistor of appropriate value $R'$ such that $IR'$ = BE.

The value of $R'$ is computed as follows:

$$BE = BD + DE$$
$$= BD + AD\tan(\phi - \theta)$$
$$= IR + IX\tan(\phi - \theta)$$
$$\text{Hence}\quad R' = R + X\tan(\phi - \theta) \qquad . \quad . \quad . \quad . \quad (4)$$

### (9.2) Comparison of Calculated and Practical Results

*Problem:* To determine the currents in the branches of a network for a 3-phase fault[1] (as in Fig. 5). Details are given in the Table below.

| Branch | Impedance | Calculated current | Analyser current | Magnitude error % | Angular error |
|---|---|---|---|---|---|
| Each generator | $1\cdot34 + j12\cdot2$ | 1274 72·3 | 1270 74 | −0·3 | +0·7* |
| AB | $0\cdot87 + j0\cdot45$ | 2270 66·2 | 2230 68 | −1·8 | +1·8 |
| BC | $1\cdot45 + j0\cdot8$ | 1660 67·8 | 1582 67 | −4·7 | −0·8 |
| CD | $1\cdot75 + j0\cdot9$ | 896 80·6 | 888 81 | −0·9 | +0·4 |
| DA | $1\cdot28 + j8\cdot74$ | 374 113·6 | 356 114·5 | −4·8 | +0·9 |
| BD | $1\cdot36 + j1\cdot36$ | 610 61·8 | 568 62 | −6·9 | +0·2 |

* It is considered that any error less than ±1° is fortuitous.

Number of trial-and-error reductions was five.
Time of solution is about 3 hours including applying the circuit to the analyser, after which the circuit is available for fault analysis at points other than C.

# DISCUSSION ON "DESIGN AND CONSTRUCTIONAL FEATURES OF A 275-kV SPECIAL-DUTY TRANSFORMER BANK"*

## NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 10TH JANUARY, 1955

**Mr. D. McDonald:** The dual and unfortunately incompatible considerations of low reactance and transportability have led the author to the choice of a shell-type construction which must have involved a great deal of work in design and manufacturing techniques, in fact an almost commercially undesirable amount of work. I wonder whether a further consideration influenced the author's decision.

In recent years, particularly in the high-voltage field, considerable publicity has been given to the merits of the shell-type transformer, but the general consensus of design opinion in this country has been that those merits have been somewhat overstated, particularly at high voltage and at the consequent high impulse test levels. It was considered possible that advantages would accrue from this construction in the particular case when exceptionally low reactance might have been required for transformers used in systems for long-distance transmission. In general, however, designers in this country have wondered to what extent the claims of the shell-type transformer were valid, and have desired an opportunity to put them to the acid test of experience.

The author is presented with an ideal opportunity, i.e. a transformer in which low reactance outweighs other technical considerations, and I wonder whether he was motivated in his decision to use the rectangular-coil shell design by the consideration that the opportunity had at last arisen to compare at high voltage the shell and the core types of construction. Has the author's experience with this type of design encouraged him

* RIPPON, E. C.: Paper No. 1690 S, August, 1954 (see **101**, Part II, p. 431).

to consider the shell-type construction for normal high-voltage power transformers?

Turning from the general to the particular, there are a few points I would like to make.

Was consideration given to a two-limb wound-core type of construction, or to a single-limb wound-shell type of construction with circular windings?

I am somewhat worried by the method of determining the voltage test levels. From the impulse standpoint there is a tendency to suggest that the level was related to that generally accepted for apparatus operating on 275 kV circuits, but surely it should be related only to switching, and not lightning, surges? Thus if the r.m.s. output voltage of the transformer is 156 kV, one would expect the maximum amplitude of transient voltages to be this voltage multiplied by $\sqrt{2}$ in order to convert to peak; multiplied by 2 to account for displacement of the voltage wave; and by $1 \cdot 5$ to allow for one phase opening prior to the other two during 3-phase testing. This gives an amplitude of transient voltages of 660 kV (peak), assuming current chopping at zero time. With an increase of 20% owing to chopping before zero time, one would anticipate a maximum amplitude of approximately 800 kV to earth, and this is the level indicated in the paper. One would think that the impulse test level should be related only to this maximum amplitude of switching surge, and I felt, consequently, that the references to the impulse test levels of 275 kV systems were a little confusing.

From the power-frequency standpoint the induced-voltage test of 370 kV (r.m.s.) seems low compared with the relatively high impulse test level established, and I wonder whether the author would comment on the selection of this latter level.

It is indicated that the maximum flux density was limited in order to enable the transformers to be used to check switching magnetizing currents, but since the construction is not normal, is this argument really valid?

Whilst it is possible to calculate the radial and axial components of the electromagnetic forces and to brace against these components, it is clear that the forces are neither purely axial nor purely radial and that a possible source of danger occurs at situations where it is not possible to achieve mechanical and electromagnetic symmetry. One such region occurs where the leads emerge from the winding, but although it is difficult from the paper to assess the effect of the inclination and support of the leads, it is very interesting to note and commend the careful radiographic tests made by the author in these localities.

It is unfortunate, after all the individuality shown in the design and manufacture of these units, that circumstances finally prohibited their being satisfactorily proved by actual impulse tests. I feel sure that the author would be the first to agree that one cannot replace or justify a test result or a test level by synthetic means, no matter how elaborately or carefully performed.

**Mr. E. C. Rippon** (*in reply*): A shell type of construction with rectangular coils was chosen because its characteristics provided the best engineering compromise to fulfil the specified conditions, coupled with the fact that since 1934 very good operating service has been obtained with similar banks of lower-voltage shell-type transformers.

On the general question of the application of shell-type transformers to e.h.v. transmission, I would refer Mr. McDonald to my Chairman's Address before the North-Eastern Centre,* when I made the following prediction:

> The use of multi-layer concentric-winding designs will increase rapidly for 3-phase transformers and particularly for auto-transformers. Graded shell-type transformers will also play a leading part in the e.h.v. field; when very large bank outputs are required, single-phase shell-type transformers may well be the ultimate engineering solution.

I would add that I am still of the same opinion.

Core-type designs were considered and rejected (see Section 3.2). Shell-type transformers with circular windings were not considered, since, in my experience, this type of winding cannot be so readily braced as rectangular coils; furthermore, the latter type always results in a more compact overall design.

The test levels assigned to these transformers were, of course, established by the company operating the testing station, and whilst the impulse test level chosen was higher than that generally associated with power systems in which switching surges might be expected to reach 800 kV to earth, the power-frequency test was, for economic reasons, kept as low as possible. Mr. McDonald will be well aware that it is not general practice to apply to e.h.v. testing transformers of any kind, power-frequency induced tests as high as those applicable to power transformers of the same voltage rating.

The maximum operating flux density was not limited in order to enable the transformers to be used to check switching magnetizing current; the possibility of performing such tests was cited in Section 3.4 as an incidental advantage.

Whilst I would agree with Mr. McDonald that there is no complete substitute for a full-voltage impulse test on a transformer, I cannot concur with his implication that model testing based on r.s.o. distribution tests on a finished unit is valueless. Such tests do give some indication of the designed impulse strength of the insulation assemblies.

* Rippon, E. C.: "North-Eastern Centre: Chairman's Address," *Proceedings I.E.E.*, January, 1952, (99, Part I, p. 18).

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Paper No. 1870 S
Dec. 1955

# THE SOLUTION OF GAS IN OIL DURING TRANSFORMER FILLING

By E. B. FRANKLIN, Associate.

(*The paper was first received* 15*th December*, 1954, *and in revised form* 21*st March*, 1955.)

## SUMMARY

The importance of thorough impregnation of transformer insulation with oil is emphasized. Means of doing this and of removing inevitably formed pockets of gas or air are stated. The solution of gas in oil is revealed as a major factor.

Certain filling methods in current use are examined and recommendations are made for filling with oil using $CO_2$ to produce better results.

## LIST OF PRINCIPAL SYMBOLS

$v_o$ = Volume of oil.
$v_{oa}$ = Volume of oil adjacent to a pocket.
$v_p$ = Volume of pocket.
$v_{ci}$ = Initial volume of $CO_2$ in the system.
$v_{ai}$ = Initial volume of air in the system.
$p$ = Partial pressure of gas on oil.
$p_a, p_c$ = Partial pressure of air and $CO_2$ respectively.
$p_f$ = Pressure applied during filling.
$p_s$ = Static pressure.
$p_g$ = Partial pressure of gas in solution.
$p'_g$ = Initial values of $p_g$.
$p_{ga}, p_{gc}$ = Partial pressure of air and $CO_2$ in solution respectively.
$p'_{ga}, p'_{gc}$ = Initial values of $p_{ga}$ and $p_{gc}$.
$k_b$ = Bunsen coefficient, defined as the volume of gas, reduced to 760 mm Hg and 0° C, in solution in unit volume of oil at a partial pressure of 760 mm Hg.
$k_a, k_c$ = Bunsen coefficient for air and $CO_2$ in oil respectively.
All pressures are in absolute units.

## (1) INTRODUCTION

That a modern h.v. transformer requires the insulation structure to be thoroughly oil-impregnated and free from any pockets of trapped gas has been stressed, especially as a result of experience with impulse testing.

Effective filling with oil, namely in such a manner as to bring about the conditions mentioned, is a factor in bringing the insulation up to strength that cannot be too strongly emphasized. As an example of this it has even been found that transformers having failed under impulse test can in some cases be made to withstand the test by draining away the oil and refilling in such a was as to eliminate trapped gas, no modification to the insulation assembly being necessary. Briefly, many failures during test can be attributed to trapped gas, and with trends towards more rigorous testing the impregnation of the insulation with oil is of increasing importance.

Voids in insulation have been the subject of recent study.[13,14,15,16] Their presence may be the cause of corona even at normal service voltages, and this has long been recognized as a possible source of damage on the insulation surface.[11] A common case is a series arrangement of air-gap and solid insulation, the air-gap being subject to electric stress in proportion to the dielectric constant of the insulation in series with it. Corona may erode the surface of the solid insulation, progressively, reducing its thickness and finally leading to puncture.[12] It has been stated that corona is probably the most important factor in reducing the electric strength of solids with increasing time of voltage application.

Now it will be conceded by most transformer engineers that, even after carefuly study of the disposition of insulating angles and barriers in h.v. transformers, gas-retaining pockets cannot be avoided in practice, and that the impregnation with oil of large sections of Fullerboard or paper insulation (a feature of modern h.v. transformers) presents formidable difficulties in some cases.

It is realized that drying and filling processes are often intimately connected, but the paper deals with filling only.

## (2) METHODS OF REMOVAL OF GAS OR AIR

Fig. 1(*a*) represents a cross-section of a supposed pocket in the insulation that will firmly trap gas as the oil level rises above its lower edges. Reference to this most simple form will be made to facilitate explanation of gas removal; a pocket might, however, well be a dry region in the centre of a solid mass of insulating material, or occur as in Fig. 1(*b*).

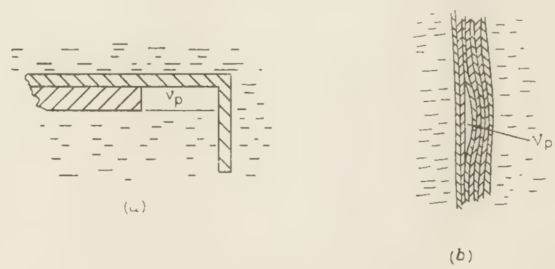


**Fig. 1.**—Pockets of trapped gas in transformer insulation.

There are two ways of reducing or completely eliminating the volume of trapped gas from a pocket. One way is by the application of a reduced pressure to the top of the tank, the reduction of volume depending on the value of reduced pressure and the conditions under which it is applied, i.e. during or after filling with oil. The volume of gas (at normal pressure) remaining in the pocket immediately after complete filling and reduced pressure treatment is $p_f v_p$ where $v_p$ is the whole volume of the pocket and $p_f$ is the applied pressure at the pocket. In the absence of zero applied pressure—and in many instances nothing like this is approached, especially for large transformers—the possibility of complete elimination of gas in the pocket depends on another process, that of causing it to be dissolved in the oil, and because this is the only means of complete removal in practice it is therefore of some importance.

## (3) THE SOLUTION OF GAS IN OIL

Surprisingly large amounts of gas can be absorbed by oil under certain conditions. The amount at normal pressure and temperature is expressed by the Bunsen coefficient, which is defined as the volume of gas reduced to 760 mm Hg and 0° C

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Mr. Franklin is with the Savoisienne Ateliers de Construction de Transformateurs de la Compagnie Générale d'Électricité.

absorbed by unit volume of liquid at a partial pressure of 760 mm Hg. The solution of gas in oil also follows Henry's law, i.e. the solubility at a given temperature is directly proportional to the partial pressure of the gas, at least for a limited pressure range. Thus the volume of gas (at normal temperature and pressure) in solution is given by $pk_bv_o$.

The value of $k_b$ has been determined by many experimenters[2,3,5,10] and representative figures for transformer oil are

$$\left.\begin{array}{r} N_2 = 0\cdot083 \\ \text{Air} = 0\cdot094 \\ CO_2 = 1\cdot0 \end{array}\right\} \text{at } 25^\circ\text{ C}$$

The variation of solubility with temperature is small for nitrogen, practically zero for air, but large for $CO_2$, for which the coefficient is about $0\cdot5$ at 100° C.[3]

### (3.1) Capacity of Oil to Dissolve Gas

The additional volume of gas that a given volume of oil can dissolve depends of course largely on the initial partial pressure of gas in solution, i.e. the initial degree of saturation. The relation $(p - p_g')k_bv_o$ gives the volume that the oil will further absorb.

## (4) AN EXAMINATION OF FILLING METHODS

In order to show their relative worth in the light of what has already been stated and to bring out certain important points, several filling methods are now examined.

*Method A.*—The transformer is filled with air-saturated oil at normal pressure. After filling, the volume of the air enclosed in the supposed pocket is $v_p$, but since there may be a head of oil acting on the pocket the actual pressure is $1 + p_s$. Solution of air may take place in a very small degree because the air pressure in the pocket is higher than the pressure of gas in solution by an amount equal to the static head, and the volume of air that may be dissolved locally is $p_sk_av_{oa}$, $v_{oa}$ being an undefined quantity of oil adjacent to the pocket. Obviously this method of filling may result in large volumes of trapped gas remaining.

*Method B.*—This is the same as method A, except that after the oil is up to level a reduced pressure is applied on the oil (i.e. to the conservator). The pressure reduction is transmitted to the pocket and the volume of air is increased; this will cause an escape of air around the bottom edges of the pocket, provided, of course, that the application of reduced pressure results in a pocket pressure less than normal. After release to normal the volume of trapped gas will be $(p_f + p_s)v_p$.

This method may be considered an improvement on method A because some air is released by the application of the reduced pressure. Free bubbles in suspension are also brought to the surface. The important fact, however, is that $p_{ga}$ will be only slightly reduced, if at all, since it is known from experience that the mere application of reduced pressure on still oil does not effectively remove gas in solution. Large amounts of trapped air will therefore be left.

*Method C.*—The transformer is subject to reduced pressure and the oil is let in while this is maintained. As the oil rises past the bottom edges of the pocket it will enclose a volume $v_p$ of gas at pressure $p_f$; when the full oil level is reached and the applied pressure is returned to normal, therefore, the volume of trapped gas remaining is $p_fv_p$.

During this filling there will be some degassing of the oil (lowering of $p_{ga}'$) depending on how the oil is let in. This makes possible the complete removal of the remaining trapped gas. The volume of gas that can be absorbed after the return to normal of the pressure in the pocket is $(1 - p_{ga}')k_av_{oa}$.

## (5) INCREASING THE EFFECT OF SOLUTION

It is obviously desirable to utilize to the full the effect of solution, and the power to absorb more gas depends first on lowering the initial value of $p_g$, i.e. degassing the oil. This can be done in separate plant, and after such treatment the oil should not be exposed to normal pressure for long periods, otherwise much of the benefit of degassing will be lost. In the absence of special plant the following method is recommended where the trapped gas is air or nitrogen.

During filling the surface area of the oil exposed to the reduced pressure should be extended by spraying in the oil at the top of the main tank, or even by directing the incoming oil-stream on to the tank wall so that it floods a large surface.

Reducing the rate of introducing the oil will also help the degassing.

The ratio $p_g'/p_f$ might be called the degassing factor; useful information on this factor can be obtained from sealed transformers where the pressure during heat runs depends on the value of $p_g'$ at the time of sealing.[8]

The second way of increasing the volume of gas absorbed is obviously to arrange for the gas initially present to have a high Bunsen coefficient. Air is slightly better for this purpose than nitrogen, but the figure for $CO_2$ far exceeds those for air or nitrogen, and in fact oil can absorb its own volume of $CO_2$ at normal pressure and at 20° C.

## (6) COMPARISON OF VOLUMES OF GAS REMOVED

The advantage in having the pockets initially filled with $CO_2$ instead of air before filling with oil is conveniently shown in Figs. 2 and 3.

Fig. 2 gives the volume of pocket that could be entirely cleared of trapped gas in terms of volume of oil considered active, i.e. when

$$(1 - p_g')k_cv_{oa} = v_pp_f \text{ for } CO_2 \quad . \quad . \quad . \quad (1)$$

and

$$(1 - p_{ga}')k_av_{oa} = v_pp_f \text{ for air} \quad . \quad . \quad . \quad . \quad (2)$$

All values of $v_p/v_{oa}$ for air and $CO_2$ initially present, are shown. The elimination of the gas is achieved by a combination of low pressure applied during filling and solution in the oil. A practical evaluation of this curve indicates that with an applied vacuum of 380 mm Hg during filling and with $CO_2$ as the occupying gas, a given quantity of degassed oil destined to occupy a volume of paper insulation could, in fact, clear a pocket of more than twice its own volume entirely of gas. This is more than eleven times as effective as if the occupying gas were air.

Eqn. (1) is valid for cases where solution leads to the complete occupation of the pocket by oil. When this condition is not fulfilled (depending on the particular volumes and pressures) an exchange of gases between pocket and adjacent oil may be involved. Thus in Fig. 2 the pocket volume $v_p$ is taken as equal to the active oil volume $v_{oa}$. This rather speculative assumption might well be true if the access of the main body of oil to the pocket were restricted. Further, it is assumed that air alone is initially present in solution; this also is likely to be roughly true in practice.

The gas finally removed is found by calculating the final value of $p_{gc}$ in the oil, and from this the volumes are easily found.

For equilibrium, $p_c/p_{gc} = p_a/p_{ga} = 1$, and if $p_{gc} + p_{ga} = 1$ the final value of $p_{gc}$ is given by

$$p_{gc} = \frac{v_{ci} - p_{gc}k_cv_{oa}}{(v_{ci} - p_{gc}k_cv_{oa}) + [v_{ai} - (1 - p_{gc})k_av_{oa}]} \quad . \quad (3)$$

where $v_{ci}$ = the initial volume of $CO_2$ in the system,

$= v_pp_f$ with $CO_2$ in the pocket only,

and $\sum v_{ai}$ = the initial volume of air in the system,

$= v_{oa}k_a p'_{ga}$ with air in solution only.

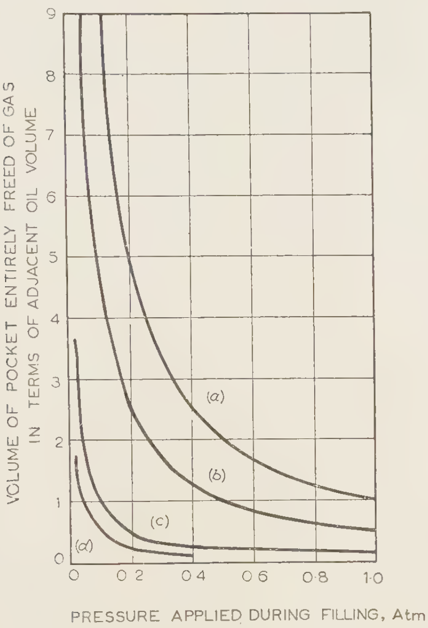


**Fig. 2.**—Relation between filling pressure and volume of pocket freed of gas in terms of oil volume.

(*a*) Initial gas $CO_2$, $p'_g \cdot = \cdot 0$
(*b*) Initial gas $CO_2$, $p_{ga} = 0{\cdot}5$
(*c*) Initial gas air, $p'_{ga} = 0$
(*d*) Initial gas air, $p'_{ga} = 0{\cdot}5$

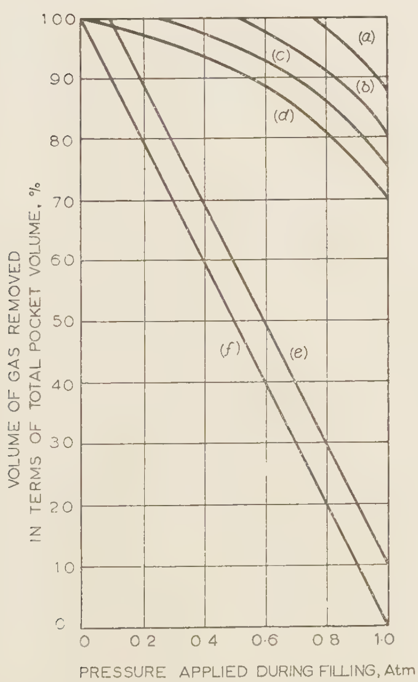


**Fig. 3.**—Relation between filling pressure and volume of gas removed in terms of volume of pocket.

$V_p = V_{oa}$
(*a*) Initial gas $CO_2$, $p'_{ga} = 0{\cdot}25$
(*b*) Initial gas $CO_2$, $p'_{ga} = 0{\cdot}5$
(*c*) Initial gas $CO_2$, $p'_{ga} = 0{\cdot}75$
(*d*) Initial gas $CO_2$, $p'_{ga} = 1{\cdot}0$
(*e*) Initial gas air, $p'_{ga} = 0$
(*f*) Initial gas air, $p'_{ga} = 0{\cdot}5$

The equation can then be solved by taking

$$a = k_c - k_a$$
$$b = k_a - k_c - p_f - p'_{ga}k_a$$
$$c = p_f$$

in the usual expresssion

$$p_{gc} = \frac{-b \pm \sqrt{(b^2 - 4ac)}}{2a} \quad . \quad . \quad . \quad (4)$$

In this case there is exchange of gases between the liquid and gas phase. The amount removed is compared in the diagram with that removed when air was the initial gas in the pocket.

The advantage of $CO_2$ over air is again marked. For filling conditions in which the oil is initially saturated with air, with no reduction of pressure during filling and with $CO_2$ as the initial pocket gas, 70% of the pocket is cleared. This compares with zero for a pocket initially containing air.

In the interest of simplicity air has been treated as a single gas. This introduces an error in the calculation for $p_{gc}$ gas, but the error is negligible.

## (7) TIME FOR SOLUTION TO OCCUR

It is quite wrong to consider a unit as ready for test immediately after the release of vacuum.

With reduced-pressure filling, solution takes place only after release to normal of the applied pressure, and it is important that time be allowed for its completion. Fig. 4, from Martin

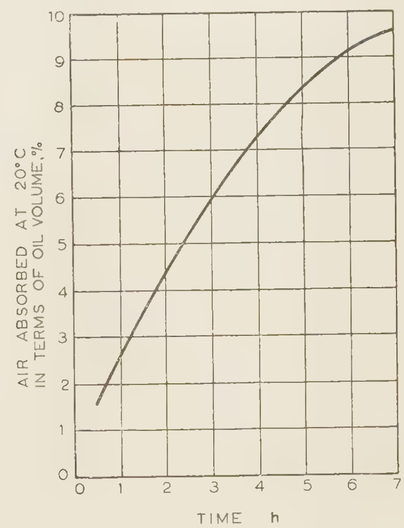


**Fig. 4.**—Absorption of air by degassed transformer oil.

Volume of sample, 100 cm³.
Surface area of sample, 70 cm² approximately.

and Thompson, shows that the rate of solution of air by still oil may be rapid. However, it must be stressed that for this example the surface/depth ratio is large. Depending as it does on this ratio the rate may be expected to have a wide variation. When an exchange of gases between the liquid and gas phases is involved longer time for equilibrium is probably required. No figures for this are yet available.

## (8) FILLING TECHNIQUE USING $CO_2$

Only the fundamentals of this method are stated here. The first object is to replace as much air in the transformer as possible with $CO_2$, taking advantage of the fact that $CO_2$ is about 1·5 times as heavy as air. The sequence of operations is as follows:

(1) $CO_2$ is admitted slowly at the bottom of the tank to displace air.

(2) Reduced pressure is applied and then released by again letting in $CO_2$ to increase the percentage further.

(3) Oil (preferably degassed) is admitted rapidly at the bottom, but with a minimum of agitation in order to keep to a minimum the gas absorbed during filling. To retard solution during this stage there may be some advantage in using hot oil with a reduced Bunsen coefficient. Obviously, for best results this operation should be done under reduced pressure.

(4) Time is allowed at normal pressure for trapped gas to be absorbed. This is most important.

The purpose of the third operation is to have oil up to normal level (with the upper surface of the oil in minimum contact with gas or air) and in a condition to absorb the maximum amount of $CO_2$ that may be trapped in the insulation.

Although large amounts of $CO_2$ can be dissolved even by air-saturated oil, there is still very good reason to use highly degassed oil. An alternative method deserving consideration when equipment is limited is the use of relatively simple apparatus for degassing, through which oil from the filled transformer is circulated, and this without need for vaccum on the main tank. By this means, $CO_2$ from the insulation structure is removed by solution in the continuously circulating oil in which the partial pressure of gas in solution is continually being reduced by the external plant. Simple tests could be made during the processing to determine the degree of degassing reached.

## (9) FINAL AMOUNT OF $CO_2$ IN THE OIL

In breather-type transformers, where oil is in communication with the atmosphere, $CO_2$ absorbed during filling would eventually be expelled. With a difference existing between the partial pressure of $CO_2$ in solution and that in the atmosphere there would be an exchange of gases between the oil and the atmosphere tending to establish equilibrium between the partial pressures. The rate of exchange would depend on the difference of the partial pressures, on the oil/atmosphere interfacial area and on the oil agitation. When exchange had ceased and equilibrium had been reached the volume of $CO_2$ in solution would be $p_c k_c v_o$, $p_c$ being the partial pressure of $CO_2$ in the atmosphere. This is so low that negligible $CO_2$ would remain in solution.

## (10) SUPERSATURATION OF OIL WITH $CO_2$

If during filling at an ambient temperature of, say, 20° C the oil is allowed to absorb an appreciable quantity of $CO_2$, there is a possibility of supersaturation at higher temperatures because of the change in Bunsen coefficient for $CO_2$. In the extreme and most unlikely case where the oil is allowed to become saturated with $CO_2$, the degree of supersaturation in a following heat run may be undesirable, since the electric strength of the oil is likely to be lowered.[8] The Buchholz protective device would probably operate because of release of gas from the supersaturated oil in the main tank. Conditions conducive to supersaturation are an extremely slow filling rate with degassed oil, and pressure near to normal during filling.

It is interesting to note that the electric strength of oil saturated with $CO_2$ is found by Clark[2] to be a little higher than that of oil saturated with air for rapidly applied voltages, and slightly lower for one-minute values.

## (11) EFFECT ON TANK DESIGN

It has been shown that $CO_2$ assists impregnation to such an extent that lower degrees of vacuum during filling might be considered. As a result, tanks could be lighter in construction. Many manufacturers have the means to dry and fill transformers in their works with the aid of a large vacuum vessel, thus obviating the need for the transformer tank to withstand vacuum. Considerable economy in construction and transport would result if thorough impregnation of the insulation structure were possible without high vacuum. It is likely that this can be achieved by dispatching the transformer filled with $CO_2$. However, further experience is necessary before renouncing the need for as high a vacuum as possible for filling h.v. units.

With a vacuum of about 310 mm Hg applied during filling, the possibility of undesirable supersaturation at high temperatures already mentioned is avoided even if the oil is allowed to become saturated by the $CO_2$ during filling. As already pointed out this is unlikely in practice, so that lower values might be envisaged.

## (12) CONCLUSION AND ACKNOWLEDGMENTS

For most cases in practice the only sure means of completely removing gas trapped in the transformer structure is by its solution in the oil. The use of degassed oil for filling is therefore most desirable and should be a fundamental part of modern technique. Solution may be increased greatly by the use of $CO_2$ in the filling process. Moreover, since conditions at site are not always favourable for filling, including degassing of oil and the application of vacuum, the saturation of the insulation structure would be aided if the new transformer were delivered filled with $CO_2$. Since it is an excellent protective gas[9] it should be used instead of nitrogen for this purpose.

Thanks are due to the Director, Savoisienne Ateliers de Construction de Transformateurs de la Compagnie Générale d'Électricité, for permission to publish the paper.

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Paper No. 1910 S
Dec. 1955

# MULTIPLE FAULT ANALYSIS OF DELTA-STAR TRANSFORMER BANKS

By J. H. BANKS, M.Sc., Graduate.

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## SUMMARY

The paper briefly describes the recent method advocated by J. C. Neupauer in America for dealing with the simultaneous application of single-line-to-earth faults on opposite sides of a delta-star transformer bank, and proceeds to compare this method with matrix methods of attack based on the work of Kron. The comparison of the two methods of approach demonstrates the inherent advantages possessed by the matrix treatment.

The classical method of solution involves a large amount of non-standard computation, and necessitates the employment of technical staff throughout. On the other hand, a swift formulation of the problem in matrix terms permits the mechanical solution to be performed by automatic means, or alternatively, by clerical staff.

Neupauer's method cannot be readily extended to the study of simultaneous dissymmetries other than earth faults; the application of matrix techniques, however, causes no further complication in principle, and conciseness is retained.

This versatility is illustrated by applying the matrix methods to the case of the simultaneous application of an earth fault and a double-line-to-earth fault on opposite sides of the transformer bank.


## LIST OF SYMBOLS

$I_{a1}$, $I_{a2}$ and $I_{a0}$ = Positive-, negative- and zero-sequence components of current on the delta side of the transformer bank.

$I_{A1}$, $I_{A2}$ and $I_{A0}$ = Corresponding sequence components of current on the star side of the transformer bank.

$I'_{a1}$, $I'_{a2}$ and $I'_{a0}$ = Positive-, negative- and zero-sequence components of delta winding currents referred to the star side of the transformer bank.

$\boldsymbol{V}$, $\boldsymbol{I}$ and $\boldsymbol{Z}$ = Voltage, current and impedance matrices, respectively, of the system in terms of phase quantities.

$\boldsymbol{V}'$, $\boldsymbol{I}'$ and $\boldsymbol{Z}'$ = Voltage, current and impedance matrices, respectively, in terms of symmetrical-component parameters of the system with balanced faults.

$\boldsymbol{V}''$, $\boldsymbol{I}''$ and $\boldsymbol{Z}''$ = Voltage, current and impedance matrices, respectively, in terms of symmetrical-component parameters of the system with unbalanced faults.

$\boldsymbol{C}$ = Connection matrix.

$\overline{\boldsymbol{C}}_t$ = Complex conjugate of the transpose of $\boldsymbol{C}$.

1, 2 and 0 = Subscripts denoting positive, negative and zero phase-sequence components, respectively.

$a = -0\cdot5 + j0\cdot866$.

## (1) INTRODUCTION

The occurrence of multiple faults on 3-phase power systems may give rise to abnormal over-voltage and resultant fault-current distributions, and may therefore be an important consideration when prescribing protective-gear limits.

The problem is best approached by changing the system of reference from phase quantities to the symmetrical components of Fortescue, thus permitting the equivalent single-phase circuit to be constructed before commencing analysis. The conventional method of solution adopted by Neupauer[1] for the investigation of simultaneous faults on delta-star transformer banks entails a preliminary simplification of the symmetrical-component equivalent networks. The simplest equivalent interconnected network having been derived, the performance of the network is described by forming the steady-state equations of voltage using Kirchhoff's laws. These equations can finally be solved, since additional constraints between the various sequence currents and voltages are known by virtue of the faults applied.

The analysis is straightforward, but the amount of computation is great. The solution is considerably complicated when one fault is unsymmetrical with respect to phase *a*. Now that automatic computing machines are fully developed, the manipulation of matrices can be performed by these machines. Standard programmes of the operations to be performed by the machine have been derived, and include the inversion of matrices of very large order which are immediately applicable to a particular problem, since it is only necessary to insert the actual matrix elements at the commencement of the solution.[2,3,4]

In order to use these machines for the solution of electrical circuits, the impedance and voltage matrices of the network are required. Accordingly, once the interconnected equivalent sequence network for a faulted transformer has been derived, no further simplification of the circuit is necessary before applying matrix techniques. The impedance matrix is most easily obtained using Stigant's rule[5], and Sections 4 and 5 illustrate the application of the rule to the multiple-faulted transformer. The presence of phase shift, imposed by the fault constraints, incurs no further complication whatsoever.

An alternative matrix method based on the work of Kron[6] is described in Section 2.3, which enables the impedance and voltage matrices to be derived from those pertaining to a related but much simpler network, called the "primitive network." The relations between the matrices of the primitive and actual networks as deduced by Kron are restated in Section 2.2.

The primitive network used is the symmetrical-component equivalent circuit of the system, all unsymmetrical faults having been changed to a balanced condition. The positive-, negative- and zero-sequence networks are now separate and distinct from one another, and their impedance matrix is easily written down using Stigant's rule. In order to transform the matrices of the primitive network to those of the equivalent symmetrical-component circuit of the system with the unsymmetrical faults, a connection matrix is required which shows the relationships which exist between the sequence components of the fault currents by virtue of the unsymmetrical nature of the faults.[7] Once the impedance matrix and the constraint matrix have been derived from the primitive network, the solution of the problem follows routine matrix methods, and can therefore be performed by a digital computing machine or by clerical staff without further intervention from the engineer.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Mr. Banks is with the General Electric Co., Ltd., Witton.

## (2) FUNDAMENTAL PROCESSES

### (2.1) Stigant's Rule

Stigant's rule enables the impedance matrix of a network to be written down directly by inspection of the network. The paths of the independent mesh currents are chosen to suit the problem under consideration, and are delineated on the network. The elements of the impedance matrix are then given by

(*a*) A diagonal element such as $Z_{rr}$ is the total impedance of the path of the *r*th mesh current.

(*b*) A non-diagonal element such as $Z_{rn}$ is the impedance common to the *r*th and *n*th mesh currents. It is positive if $I_r$ and $I_n$ flow through the impedance in the same direction, and negative if they flow in opposite directions.

(For linear bilateral networks, the impedance matrix is symmetrical and $Z_{rn} = Z_{nr}$.)

As an example of the use of the rule, the equations of the network shown in Fig. 1 are written as

$$\begin{bmatrix} V_x \\ V_x - V_y \end{bmatrix} = \begin{bmatrix} Z_x + Z_v & Z_x \\ Z_x & Z_x + Z_y \end{bmatrix} \cdot \begin{bmatrix} I_x \\ I_y \end{bmatrix} \quad . \quad (1)$$

directly from the network.

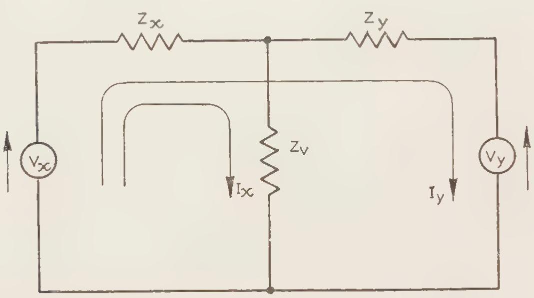


**Fig. 1.**—Two generators in parallel supplying a load.

### (2.2) Interconnection of Networks

Kron[6] has shown that if the equations of a network $V' = Z'I$ are known, the equations of another network derived from the first (primitive) by changing the connections, but without increasing the number of independent meshes, may be obtained in the following manner: The relationship between the mesh currents of the primitive network, $I'$, and the mesh currents of the network, $I''$, is written as

$$I' = CI'' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $C$ is the "connection matrix."

The new voltage matrix $V''$ is given by

$$V'' = \overline{C}_t V' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and the new impedance matrix $Z''$ is given by

$$Z'' = \overline{C}_t Z' C \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where $\overline{C}_t$ is the complex conjugate of the transpose of $C$.

### (2.3) General Constraint Technique

The positive-, negative- and zero-sequence networks for a 3-phase system with balanced-phase impedances are separate and distinct from one another. The primitive network chosen for the calculation of the steady-state fault currents is the symmetrical-component representation of the system, all faults having been replaced by a balanced condition. The impedance matrix of the primitive network is denoted by $Z'$, and the voltage and current matrices by $V'$ and $I'$, respectively. A connection matrix $C$ is obtained by expressing in the form $I' = CI''$ the relationships between the mesh currents of the primitive network, $I'$, and the mesh currents actually necessary for the analysis, $I''$. The number of currents in $I''$ will be less than those in $I'$, owing to the relationships which exist between the sequence currents pertaining to an unsymmetrical fault.

Eqns. (3) and (4) enable the voltage and impedance matrices of the symmetrical-component representation of the unbalanced system to be calculated. The required currents may now be evaluated, either by hand using a desk calculating machine for small problems, or by an automatic digital computer for larger problems.

As a simple illustration of the method consider a generator having line $a$ short-circuited to neutral, as shown in Fig. 2. In this technique the unsymmetrical fault is replaced by a suitable balanced condition, namely the symmetrical short-circuit to neutral shown in Fig. 3. The symmetrical-component network

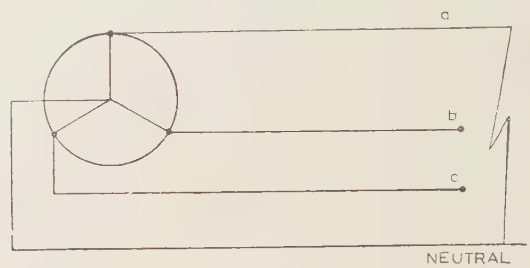


**Fig. 2.**—Three-phase generator with single line-to-neutral short-circuit.

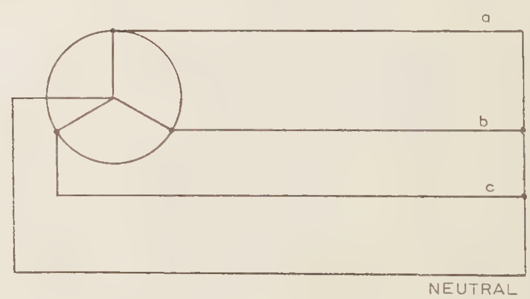


**Fig. 3.**—Three-phase generator with balanced short-circuit.

equivalent to Fig. 3 is shown in Fig. 4. The matrix equation of this network $V' = Z'I'$ is

$$\begin{bmatrix} V_1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & & \\ & Z_2 & \\ & & Z_0 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} \quad . \quad . \quad (5)$$

The connection matrix is developed in the following manner. In the original system shown in Fig. 2.

$$I_b = I_c = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Consequently from the definitions of the currents, $I_1$, $I_2$ and $I_0$ it is deduced that

$$I_1 = I_2 = I_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and the analysis may proceed in terms of one current only, e.g. $I_1$.

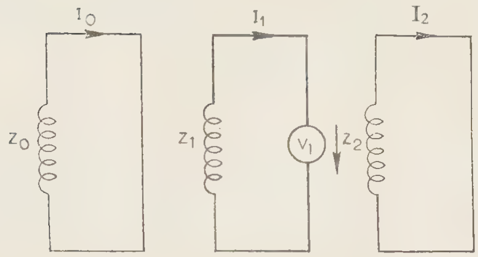


**Fig. 4.**—Symmetrical-component equivalent circuit of 3-phase generator with balanced short-circuit.

The relationships are then written as

$$\begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \cdot \begin{bmatrix} I_1 \end{bmatrix} \quad . \quad . \quad . \quad . \quad (8)$$

which is the equation

$$I' = CI'' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

so that the connection matrix $C$ is given by

$$C = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

The equations of the unsymmetrical fault are now determined from eqns. (3) and (4), and are

$$V'' = \overline{C}_t V' = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_1 \\ 0 \\ 0 \end{bmatrix}$$

Therefore $$V'' = V_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

and $$Z'' = \overline{C}_t Z' C = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} Z_1 & & \\ & Z_2 & \\ & & Z_0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

Therefore $$Z'' = Z_1 + Z_2 + Z_0 \quad . \quad . \quad . \quad . \quad . \quad (12)$$

and $$I'' = I_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

In this simple case there is one equation only, namely

$$V_1 = (Z_1 + Z_2 + Z_0)I_1 \quad . \quad . \quad . \quad . \quad (14)$$

from which $I_1$ may be calculated. The equivalent circuit is seen to be that shown in Fig. 5.

## (3) CONVENTIONAL METHOD OF NEUPAUER APPLIED TO A DELTA-STAR TRANSFORMER BANK

### (3.1) Simultaneous Line-to-Earth-Faults

The circuit diagram is shown in Fig. 6. It contains two generating sources $G_1$ and $G_2$, connected through a delta-star-connected transformer bank. The neutral point of the star-connected winding is earthed, and the systems on both sides of the transformer bank provide means for the flow of earth currents. The equivalent positive-, negative- and zero-sequence networks are shown in Fig. 7.

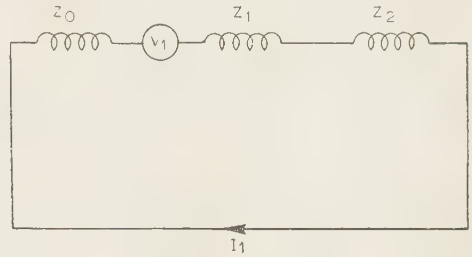


**Fig. 5.**—Symmetrical-component equivalent circuit of 3-phase generator with single line-to-neutral short-circuit.

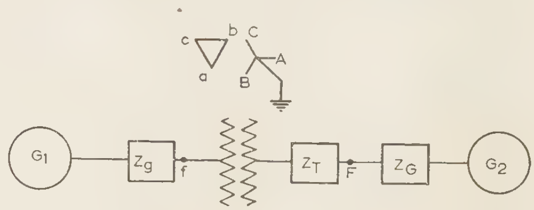


**Fig. 6.**—Single line diagrams of 3-phase power system.

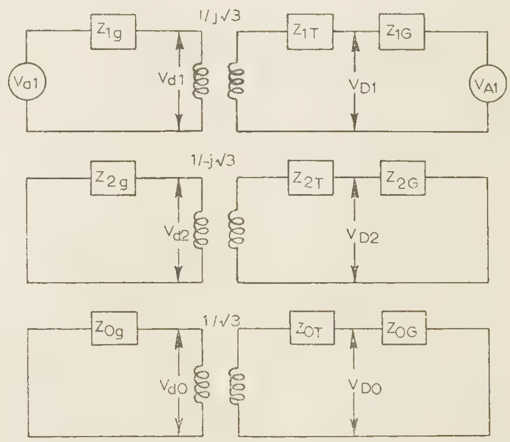


**Fig. 7.**—Symmetrical-component equivalent circuit of two 3-phase generators linked by a delta-star transformer bank.

In passing through the star-delta transformer bank, positive-sequence quantities will be shifted 90° clockwise in going from the star side to the delta side of the transformer bank. When the constraints of the two earth faults are applied the inter-connected equivalent sequence network is given by Fig. 8.

The following relations apply between the currents and voltages on the two sides of the transformer bank:

$$I_{A1} = jI_{a1}\frac{1}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$I_{A2} = -jI_{a2}\frac{1}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

$$I_{A0} = I_{a0}\frac{1}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

$$V'_{d1} = V_{D1} = jV_{d1}\sqrt{3} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

$$V'_{d2} = V_{D2} = -jV_{d2}\sqrt{3} \quad . \quad . \quad . \quad . \quad (19)$$

$$V'_{d0} = V_{D0} = V_{d0}\sqrt{3} \quad . \quad . \quad . \quad . \quad (20)$$

For the double-earth-fault case being considered the phase faulted on the delta side of the transformer bank can be regarded

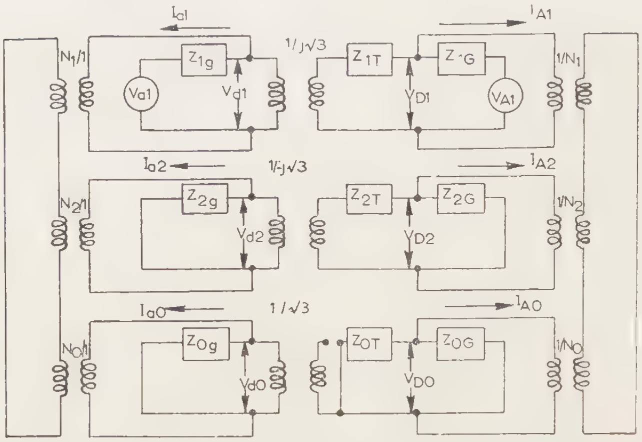


**Fig. 8.**—Interconnected sequence network for simultaneous single line-to-earth faults on opposite sides of delta-star transformer bank.

as phase *a*, and the phase faulted on the star side must then be termed *A*, *B* or *C* to represent the desired combination.

This allows the transformer ratios, $N_1$, $N_2$ and $N_0$, on the delta side of the bank in Fig. 8 all to be equal to and maintained at 1:1 and permits the use of a simplified equivalent circuit. The circuit can be further simplified by moving the phase-shifting transformers in the positive- and negative-sequence circuits to the left, thus referring the currents and voltages on the delta side of the bank to the star side. Since the terminals of the transformers coupling the sequence networks together on the delta side of the bank have also been shifted to the star side of the bank,

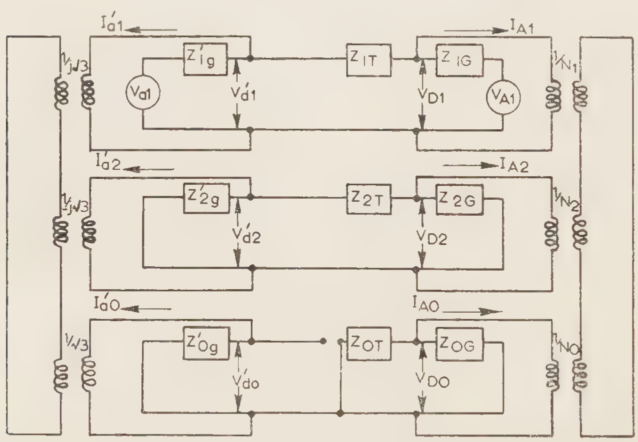


**Fig. 9.**—Interconnected sequence network with delta quantities referred to the star side of the transformer bank.

their ratios must be changed. The resulting circuit is shown in Fig. 9, in which

$$Z'_{1g} = 3Z_{1g} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

$$Z'_{2g} = 3Z_{2g} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

$$Z'_{0g} = 3Z_{0g} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

and

$$\frac{\sqrt{3}}{j}I'_{a1} = -\frac{\sqrt{3}}{j}I'_{a2} = I'_{a0}\sqrt{3} \quad . \quad . \quad . \quad . \quad (24)$$

where $I'_{a1}$, $I'_{a2}$ and $I'_{a0}$ are equal to the positive-, negative- and zero-sequence components of current on the delta side referred to the star side of the transformer bank.

Eqn. (24) may be expressed as

$$I'_{a1} = -I'_{a2} = jI'_{a0} \quad . \quad . \quad . \quad . \quad . \quad (25)$$

The current transformers may now be eliminated from the positive-sequence and zero-sequence circuits. In addition, if it is assumed that the generator voltages are equal in magnitude and phase, the terminals of $V'_{a1}$ and $V_{A1}$ can be connected.

The interconnected impedances in each sequence network may then be simplified by performing delta-star transformations,

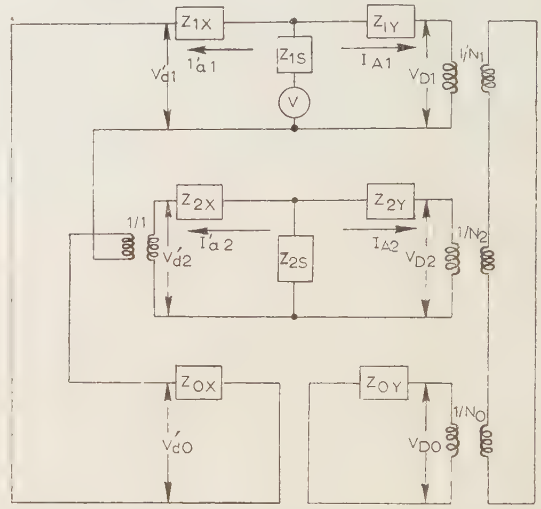


**Fig. 10.**—Final simplified equivalent circuit for simultaneous line-to-neutral short-circuits on both sides of a delta-star transformer bank.

when the final simplified equivalent network shown in Fig. 10 is obtained, in which

$$Z_{1X} = \frac{Z'_{1g}Z_{1T}}{Z'_{1g} + Z_{1T} + Z_{1G}} \quad . \quad . \quad . \quad . \quad (26)$$

$$Z_{2X} = \frac{Z'_{2g}Z_{2T}}{Z'_{2g} + Z_{2T} + Z_{2G}} \quad . \quad . \quad . \quad . \quad (27)$$

$$Z_{0X} = Z'_{0g} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

$$Z_{1Y} = \frac{Z_{1G}Z_{1T}}{Z'_{1g} + Z_{1T} + Z_{1G}} \quad . \quad . \quad . \quad . \quad (29)$$

$$Z_{2Y} = \frac{Z_{2G}Z_{2T}}{Z'_{2g} + Z_{2T} + Z_{2G}} \quad . \quad . \quad . \quad . \quad (30)$$

$$Z_{0Y} = \frac{Z_{0G}Z_{0T}}{Z_{0G} + Z_{0T}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

$$Z_{1S} = \frac{Z'_{1g}Z_{1G}}{Z'_{1g} + Z_{1T} + Z_{1G}} \quad . \quad . \quad . \quad . \quad (32)$$

$$Z_{2S} = \frac{Z'_{2g}Z_{2G}}{Z'_{2g} + Z_{2T} + Z_{2G}} \quad . \quad . \quad . \quad . \quad (33)$$

By inspection of Fig. 10 the following equations may then be formed:

$$V_{D1} = V - I_{A1}(Z_{1S} + Z_{1Y}) - I'_{a1}Z_{1S} \quad . \quad . \quad . \quad (34)$$

$$V_{D2} = -I_{A2}(Z_{2S} + Z_{2Y}) - I'_{a2}Z_{2S} \quad . \quad . \quad . \quad (35)$$

$$V_{D0} = -I_{A0}Z_{0Y} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

$$V'_{d1} = V - I'_{a1}(Z_{1S} + Z_{1X}) - I_{A1}Z_{1S} \quad . \quad . \quad . \quad (37)$$

$$V'_{d2} = - I'_{a2}(Z_{2S} + Z_{2X}) - I_{A2}Z_{2S} \quad . \quad . \quad . \quad (38)$$

$$jV'_{d0} = - jI'_{a0}Z_{0X} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

These equations may be solved to give the sequence components of fault currents once the additional relationships between the sequence components have been stated for a particular combination of phase faults.

#### (3.1.1) Simultaneous Earth Faults on Phases a and A applied at the Points f and F.

The relationships between the sequence currents and voltages are as follows:

$$I_{A1} = I_{A2} = I_{A0} \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

$$V_{D1} + V_{D2} + V_{D0} = 0 \quad . \quad . \quad . \quad . \quad . \quad (41)$$

$$I'_{a1} = - I'_{a2} = jI'_{a0} \quad . \quad . \quad . \quad . \quad . \quad . \quad (42)$$

$$V'_{d1} - V'_{d2} + jV'_{d0} = 0 \quad . \quad . \quad . \quad . \quad . \quad (43)$$

The network impedances may also be grouped as follows:

$$Z_{1S} + Z_{1Y} = Z_{1F} \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

$$Z_{2S} + Z_{2Y} = Z_{2F} \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

$$Z_{1S} + Z_{1X} = Z_{1f} \quad . \quad . \quad . \quad . \quad . \quad . \quad (46)$$

$$Z_{2S} + Z_{2X} = Z_{2f} \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

$$Z_{1S} + Z_{1Y} + Z_{2S} + Z_{2Y} + Z_{0Y} = Z_F \quad . \quad . \quad (48)$$

$$Z_{1S} + Z_{1X} + Z_{2S} + Z_{2X} + Z_{0X} = Z_f \quad . \quad . \quad (49)$$

$$Z_m = Z_{1S} - Z_{2S} \quad . \quad . \quad . \quad . \quad . \quad . \quad (50)$$

By substituting eqns. (40)–(43) into eqns. (34)–(39), two resultant equations are obtained as follows:

$$0 = V - I_{A1}Z_F - I'_{a1}Z_m \quad . \quad . \quad . \quad . \quad . \quad (51)$$

$$0 = V - I'_{a1}Z_f - I_{A1}Z_m \quad . \quad . \quad . \quad . \quad . \quad (52)$$

Solving for the currents in eqns. (51) and (52),

$$I_{A1} = V\frac{Z_f - Z_m}{Z_fZ_F - Z_m^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (53)$$

$$I'_{a1} = V\frac{Z_F - Z_m}{Z_fZ_F - Z_m^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (54)$$

Eqns. (53) and (54) in conjunction with eqns. (40) and (42) substituted into eqns. (34)–(39) yield the sequence components of the voltages at fault points f and F.

The phase voltages at the fault point on the star side of the transformer can be calculated directly by substituting eqns. (34), (35) and (36) into the equations for the phase quantities, namely

$$V_A = V_{D1} + V_{D2} + V_{D0} \quad . \quad . \quad . \quad . \quad (55)$$

$$V_B = a^2V_{D1} + aV_{D2} + V_{D0} \quad . \quad . \quad . \quad (56)$$

$$V_C = aV_{D1} + a^2V_{D2} + V_{D0} \quad . \quad . \quad . \quad (57)$$

In calculations of the phase voltages at the fault point on the delta side of the transformer the sequence components of the voltages, as obtained from eqns. (37), (38) and (39), must first be referred back to the delta side of the transformer bank by means of eqns. (18), (19) and (20) before evaluations of the phase quantities.



### (4) MATRIX METHODS OF SOLUTION

The equivalent circuit shown in Fig. 10 will be used initially. It will be shown subsequently, however, that preliminary simplification is not necessary.

#### (4.1) Use of Stigant's Rule

The current constraints of the earth fault on phase $a$ at f were given by eqn. (42), and those of the earth fault on phase $A$ at F were given by eqn. (40). The paths of the independent mesh currents may be chosen as shown by Fig. 11. From the relation-

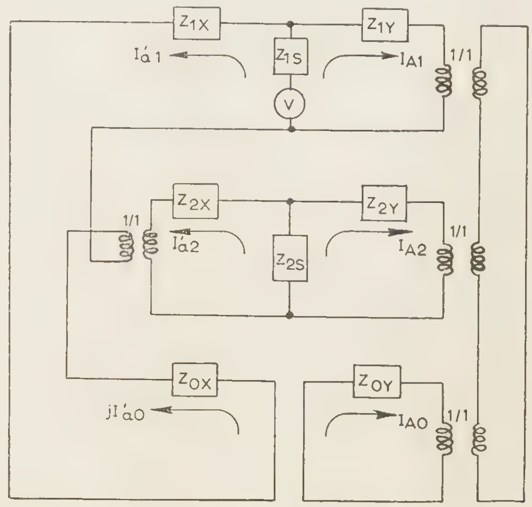


**Fig. 11.**—Final simplified equivalent circuit with mesh currents defined.

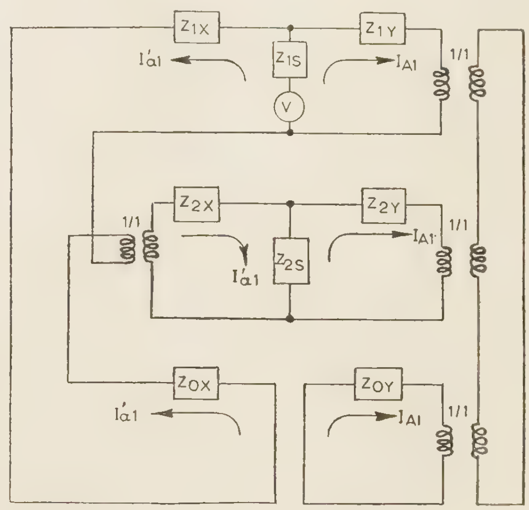


**Fig. 12.**—Final simplified equivalent circuit with mesh currents defined in terms of $I'_{a1}$ and $I_{A1}$.

ships expressed by eqns. (42) and (40), the mesh currents of the phase-$a$ fault may be expressed in terms of $I'_{a1}$, and those of the phase-$A$ fault may be expressed in terms of $I_{A1}$. Fig. 11 may therefore be replaced by Fig. 12, and Stigant's rule may be directly applied to this network.

Any diagonal element of the impedance matrix is the algebraic sum of the self (and mutual) impedances traversed by the associated mesh current. $Z_{a1'a1'}$ is consequently the algebraic sum

of the impedances traversed by the mesh current $I'_{a1}$, and is equal to

$$Z_{a1'a1'} = Z_{1S} + Z_{1X} + Z_{2S} + Z_{2X} + Z_{0X} \quad . \quad . \quad (58)$$

Similarly, the diagonal element $Z_{A1A1}$ is equal to

$$Z_{A1A1} = Z_{1S} + Z_{1Y} + Z_{2S} + Z_{2Y} + Z_{0Y} \quad . \quad . \quad (59)$$

A non-diagonal element of the impedance matrix, e.g. $Z_{a1'A1}$, may be defined as the coefficient of $I_{A1}$ in the equation of the $I'_{a1}$th mesh, and is consequently equal to the algebraic sum of all impedances traversed by both $I'_{a1}$ and $I_{A1}$. It is positive if the currents flow through the impedance in the same direction and negative if in opposite directions. $Z_{a1'A1}$ becomes equal to

$$Z_{a1'A1} = Z_{1S} - Z_{2S} \quad . \quad . \quad . \quad . \quad . \quad (60)$$

Similarly

$$Z_{A1a1'} = Z_{1S} - Z_{2S} \quad . \quad . \quad . \quad . \quad (61)$$

The matrix equation can now be written down directly as

$$\begin{array}{|c|}\hline V'_{a1} \\ \hline V_{A1} \\ \hline\end{array} = \begin{array}{|c|c|}\hline Z_{a1'a1'} & Z_{a1'A1} \\ \hline Z_{A1a1'} & Z_{A1A1} \\ \hline\end{array} \cdot \begin{array}{|c|}\hline I'_{a1} \\ \hline I_{A1} \\ \hline\end{array} \quad . \quad . \quad (62)$$

On inversion of the impedance matrix, the matrix equation for the unknown mesh currents is obtained as follows:

$$\begin{array}{|c|}\hline I'_{a1} \\ \hline I_{A1} \\ \hline\end{array} = \frac{1}{D}\begin{array}{|c|c|}\hline Z_{A1A1} & -Z_{A1a1'} \\ \hline -Z_{a1'A1} & Z_{a1'a1'} \\ \hline\end{array} \cdot \begin{array}{|c|}\hline V'_{a1} \\ \hline V_{A1} \\ \hline\end{array} \quad . \quad (63)$$

where

$$D = Z_{a1'a1'}Z_{A1A1} - Z_{A1a1'}Z_{a1'A1} \quad . \quad . \quad . \quad (64)$$

By comparison with eqns. (48), (49) and (50) it is seen that

$$Z_{A1A1} = Z_F \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (65)$$

$$Z_{a1'a1'} = Z_f \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (66)$$

$$Z_{a1'A1} = Z_{A1a1'} = Z_m \quad . \quad . \quad . \quad . \quad . \quad (67)$$

The unknown mesh currents are obtained directly by evaluating eqn. (63), giving

$$I_{A1} = V\frac{Z_f - Z_m}{Z_f Z_F - Z_m^2} \quad . \quad . \quad . \quad . \quad . \quad (68)$$

$$I'_{a1} = V\frac{Z_F - Z_m}{Z_f Z_F - Z_m^2} \quad . \quad . \quad . \quad . \quad . \quad (69)$$

### (4.2) Kron Constraint Technique

#### (4.2.1) Application to Final Simplified Network shown in Fig. 12.

Balanced faults are applied at the points f and F, as shown in the equivalent-sequence network of Fig. 13. The equivalent symmetrical-component impedance matrix may be written down by inspection as follows:

$$Z' = \begin{array}{|c|c|c|c|c|c|}\hline Z_{1X}+Z_{1S} & Z_{1S} & 0 & 0 & 0 & 0 \\ \hline Z_{1S} & Z_{1Y}+Z_{1S} & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & Z_{2X}+Z_{2S} & Z_{2S} & 0 & 0 \\ \hline 0 & 0 & Z_{2S} & Z_{2Y}+Z_{2S} & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & Z_{0x} & 0 \\ \hline 0 & 0 & 0 & 0 & 0 & Z_{0y} \\ \hline\end{array} \quad . \quad . \quad . \quad . \quad (70)$$

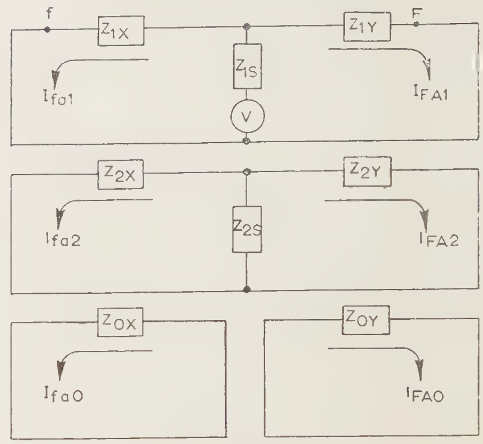


**Fig. 13.**—Symmetrical-component equivalent circuit with balanced faults applied at f and F.

The constraints imposed by the two earth faults must now be applied. The fault on phase $a$ is such that

$$I'_{a1} = -I'_{a2} = jI'_{a0} \quad . \quad . \quad . \quad . \quad . \quad (42)$$

and the fault on phase $A$ imposes the condition that

$$I_{A1} = I_{A2} = I_{A0} \quad . \quad . \quad . \quad . \quad . \quad (40)$$

With each fault expressed in terms of the positive-sequence component of current, the constraint matrix $C$ may be formed as follows:

$$C = \begin{array}{c|c|c|}
\text{mesh} & a'1 & A1 \\ \hline
f_{a1} & 1 & 0 \\ \hline
F_{A1} & 0 & 1 \\ \hline
f_{a2} & -1 & 0 \\ \hline
F_{A2} & 0 & 1 \\ \hline
f_{a0} & +j1 & 0 \\ \hline
F_{A0} & 0 & 1 \\ \hline
\end{array} \quad . \quad . \quad (71)$$

The conjugate of the transpose of $C$ becomes

$$\bar{C}_t = \begin{array}{|c|c|c|c|c|c|}\hline 1 & 0 & -1 & 0 & -j1 & 0 \\ \hline 0 & 1 & 0 & 1 & 0 & 1 \\ \hline\end{array} \quad . \quad (72)$$

and the unsymmetrical fault matrix is given by $Z'' = \bar{C}_t Z' C$

$$Z'' = \begin{array}{c|c|c|}
 & f & m \\ \hline
f & Z_{1X} + Z_{1S} + Z_{2X} + Z_{2S} + Z_{0X} & Z_{1S} - Z_{2S} \\ \hline
m & Z_{1S} - Z_{2S} & Z_{1Y} + Z_{1S} + Z_{2Y} + Z_{2S} + Z_{0Y} \\ \hline
\end{array} \; F$$

$$. \quad . \quad . \quad . \quad . \quad (73)$$

which is the impedance matrix obtained by the direct application of Stigant's rule in Section 4.1.

The voltage matrix $V'' = \overline{C}_t V'$ is given by

$$V'' = \begin{array}{|c|}\hline V \\ \hline V \\ \hline\end{array} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (74)$$

It is seen that the application of the constraint method entails no knowledge of the interconnections between the sequence networks. It is necessary to know only the constraints imposed by the applied faults.

### (4.2.2) Simultaneous Line-to-Earth Faults applied to the Network shown in Fig. 9.

#### (4.2.2.1) *Stigant's Rule Treatment.*

The paths of the independent mesh currents are chosen as shown in Fig. 14. Simultaneous earth faults on phases $a$ and $A$ will again be considered. The fault on phase $a$ has again been expressed in terms of the positive-sequence current $I'_{a1}$, and that on phase $A$ in terms of the positive-sequence current $I_{A1}$.

The diagonal element of the impedance matrix $Z_{a1'a1'}$ is seen to be

$$Z_{a1'a1'} = Z'_{1g} + Z'_{2g} + Z'_{0g} \quad . \quad . \quad . \quad . \quad (75)$$

Similarly, the diagonal elements $Z_{pp}$ and $Z_{A1A1}$ are given by

$$Z_{pp} = Z'_{1g} + Z_{1T} + Z_{1G} \quad . \quad . \quad . \quad . \quad (76)$$

and

$$Z_{A1A1} = Z_{1G} + Z_{2G} + Z_{0G} \quad . \quad . \quad . \quad . \quad (77)$$

Typical non-diagonal elements are given as follows:

$$Z_{a1'}P = + Z'_{1g} \quad . \quad . \quad . \quad . \quad . \quad (78)$$

$$Z_{a1'}Q = - Z'_{2g} \quad . \quad . \quad . \quad . \quad . \quad (79)$$

The full fault-impedance matrix is of order of 5 × 5, and is given as follows:

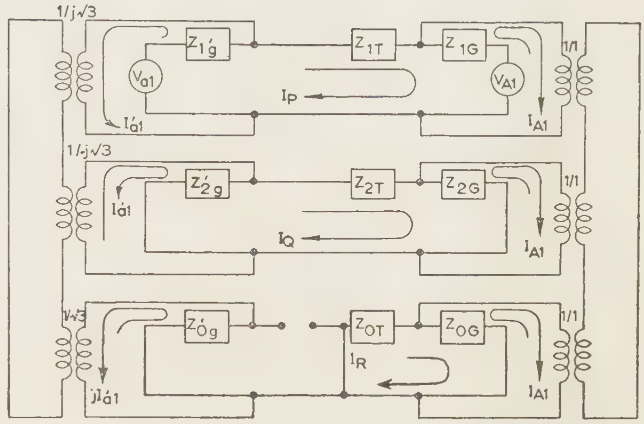


Fig. 14.—Unsimplified symmetrical-component equivalent circuit, with simultaneous line-to-neutral faults applied on both sides of the delta-star transformer bank.

$$Z'' = \begin{array}{c|c|c|c|c|c|} & a'_1 & P & Q & R & A_1 \\ \hline a'_1 & Z'_{1g} + Z'_{2g} + Z'_{0g} & Z'_{1g} & -Z'_{2g} & 0 & 0 \\ \hline P & Z'_{1g} & Z'_{1g} + Z_{1T} + Z_{1G} & 0 & 0 & -Z_{1G} \\ \hline Q & -Z'_{2g} & 0 & Z'_{2g} + Z_{2T} + Z_{2G} & 0 & -Z_{2G} \\ \hline R & 0 & 0 & 0 & Z_{0T} + Z_{0G} & -Z_{0G} \\ \hline A_1 & 0 & -Z_{1G} & -Z_{2G} & -Z_{0G} & Z_{1G} + Z_{2G} + Z_{0G} \\ \hline \end{array} \quad . \quad (80)$$

and

$$V'' = \begin{array}{|c|}\hline V'_{a1} \\ \hline V'_{a1} - V_{A1} \\ \hline 0 \\ \hline 0 \\ \hline V_{A1} \\ \hline\end{array} \quad . \quad . \quad . \quad . \quad . \quad (81)$$

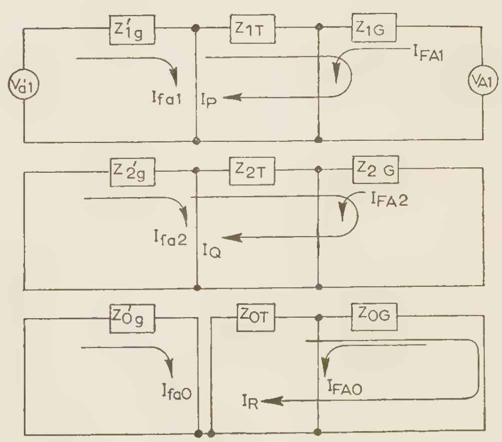


Fig. 15.—Unsimplified symmetrical-component equivalent circuit, with simultaneous symmetrical faults applied on both sides of the delta-star transformer bank.

#### (4.2.2.2) *Kron Constraint Approach.*

Balanced faults are applied at f and F, as shown in Fig. 15, and the symmetrical fault-impedance matrix is found by inspection.

| | $a_1'$ | $A_1$ | $a_2$ | $A_2$ | $a_0$ | $A_0$ | $P$ | $Q$ | $R$ |
|---|---|---|---|---|---|---|---|---|---|
| $a_1'$ | $Z_{1g}'$ | 0 | 0 | 0 | 0 | 0 | $Z_{1g}'$ | 0 | 0 |
| $A_1$ | 0 | $Z_{1G}$ | 0 | 0 | 0 | 0 | $-Z_{1G}$ | 0 | 0 |
| $a_2$ | 0 | 0 | $Z_{2g}'$ | 0 | 0 | 0 | 0 | $Z_{2g}'$ | 0 |
| $A_2$ | 0 | 0 | 0 | $Z_{2G}$ | 0 | 0 | 0 | $-Z_{2G}$ | 0 |
| $a_0$ | 0 | 0 | 0 | 0 | $Z_{0g}'$ | 0 | 0 | 0 | 0 |
| $A_0$ | 0 | 0 | 0 | 0 | 0 | $Z_{0G}$ | 0 | 0 | $-Z_{0G}$ |
| $P$ | $Z_{1g}'$ | $-Z_{1G}$ | 0 | 0 | 0 | 0 | $Z_{1g}'+Z_{1T}+Z_{1G}$ | 0 | 0 |
| $Q$ | 0 | 0 | $Z_{2g}'$ | $-Z_{2G}$ | 0 | 0 | 0 | $Z_{2g}'+Z_{2T}+Z_{2G}$ | 0 |
| $R$ | 0 | 0 | 0 | 0 | 0 | $-Z_{0G}$ | 0 | 0 | $Z_{0T}+Z_{0G}$ |

. (82)

The constraints for the two earth faults are embodied in the following connection matrix:

| | | $a_1'$ | $A_1$ | $P$ | $Q$ | $R$ |
|---|---|---|---|---|---|---|
| 1 | $f_a$ | 1 | 0 | 0 | 0 | 0 |
| | $F_A$ | 0 | 1 | 0 | 0 | 0 |
| 2 | $f_a$ | $-1$ | 0 | 0 | 0 | 0 |
| | $F_A$ | 0 | 1 | 0 | 0 | 0 |
| 0 | $f_a$ | $j1$ | 0 | 0 | 0 | 0 |
| | $f_A$ | 0 | 1 | 0 | 0 | 0 |
| | $P$ | 0 | 0 | 1 | 0 | 0 |
| | $Q$ | 0 | 0 | 0 | 1 | 0 |
| | $R$ | 0 | 0 | 0 | 0 | 1 |

. (83)

The final fault-impedance matrix is given as before by $Z'' = \overline{C}_t Z' C$, and the final voltage matrix by $V'' = \overline{C}_t V'$. It will be seen that there are no constraints applied to the currents of unfaulted meshes.

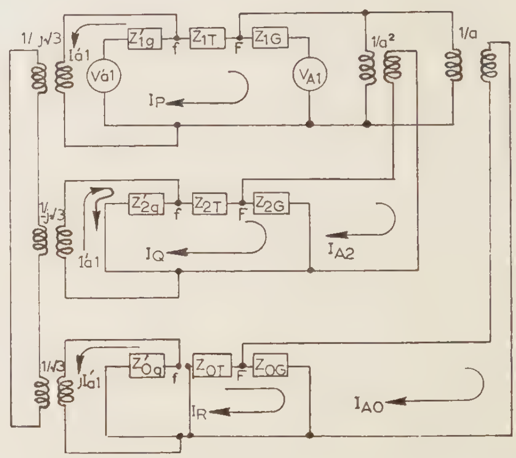

Fig. 16.—Interconnected sequence network for a line-to-neutral fault applied at f on phase $a$, and a double-line-to-neutral fault applied at F on phases $A$ and $B$.

## (5) SIMULTANEOUS LINE-TO-EARTH FAULT ON PHASE $a$ AT POINT f AND DOUBLE-LINE-TO-EARTH FAULT ON PHASES $A$ AND $B$ AT POINT F

### (5.1) Stigant's Rule Approach

The equivalent interconnected sequence network is shown in Fig. 16. The fault-impedance matrix may be obtained directly by the application of Stigant's rule, and consequently,

$Z'' =$

| | $a_1'$ | $P$ | $Q$ | $R$ | $A_2$ | $A_0$ |
|---|---|---|---|---|---|---|
| $a_1'$ | $Z_{1g}'+Z_{2g}'+Z_{0g}'$ | $Z_{1g}'$ | $-Z_{2g}'$ | 0 | 0 | 0 |
| $P$ | $Z_{1g}'$ | $Z_{1g}'+Z_{1T}+Z_{1G}$ | 0 | 0 | $-aZ_{1G}$ | $-a^2Z_{1G}$ |
| $Q$ | $-Z_{2g}'$ | 0 | $Z_{2g}'+Z_{2T}+Z_{2G}$ | 0 | $-Z_{2G}$ | 0 |
| $R$ | 0 | 0 | 0 | $Z_{0T}+Z_{0G}$ | 0 | $-Z_{0G}$ |
| $A_2$ | 0 | $-a^2Z_{1G}$ | $-Z_{2G}$ | 0 | $Z_{1G}+Z_{2G}$ | $aZ_{1G}$ |
| $A_0$ | 0 | $-aZ_{1G}$ | 0 | $-Z_{0G}$ | $a^2Z_{1G}$ | $Z_{1G}+Z_{0G}$ |

. (84)

and
$$V'' = \begin{bmatrix} V'_{a1} \\ V'_{a1} - V_{A1} \\ 0 \\ 0 \\ -a^2V_{A1} \\ -aV_{A1} \end{bmatrix} \quad . \quad . \quad . \quad . \quad . \quad . \quad (85)$$

### (5.2) Kron Constraint Solution

The symmetrical fault impedance is again given by eqn. (82). The constraints imposed in this instance are as follows:

*Fault at f.*— $I'_{a1} = - I'_{a2} = jI'_{a0}$

*Fault at F.*— $I_{A1} = - a(I_{A2} + aI_{A0})$

The constraint matrix may therefore be formed directly by analysing in terms of $I'_{a1}$, $I_{A2}$ and $I_{A0}$ and the unconstrained mesh currents $I_P$, $I_Q$ and $I_R$.

$$C = \begin{array}{c} \\ f_{a1} \\ F_{A1} \\ f_{a2} \\ F_{A2} \\ f_{a0} \\ F_{A0} \\ P \\ Q \\ R \end{array} \begin{array}{c} \begin{array}{cccccc} a'_1 & P & Q & R & A_2 & A_0 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -a & -a^2 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ j1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \end{array} \quad . \quad . \quad . \quad . \quad . \quad (86)$$

The final fault-impedance matrix is given by $Z'' = \overline{C}_t Z'C$, and the final voltage matrix $V''$ is equal to $\overline{C}_t V'$.

## (6) CONCLUSION

Matrix methods may therefore be applied directly to the equivalent sequence networks without preliminary simplification of the networks. All types of dissymmetry may be analysed without complication in principle. A knowledge of the imposed constraints is all that is required before applying the Kron constraint method, whilst the interconnection of the sequence networks must be carried out before applying the Stigant's-rule method. In contrast, the conventional methods employed by Neupauer are inherently non-standard and entail a large amount of network manipulation and the solution of non-standard equations by substitution.

Whilst the presence of phase shift in the equivalent network is no obstacle to the matrix solutions when employing the symmetrical components of Fortescue, the extension of the method to networks defined by the $\alpha$, $\beta$, 0 components of Clarke[8] is of interest, and is treated briefly in Section 9.

## (7) ACKNOWLEDGMENTS

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## (9) APPENDIX

### (9.1) Use of α, β, 0 Components

The properties of the Clarke system of components are described in Reference 8, Chapter 10, and their application to

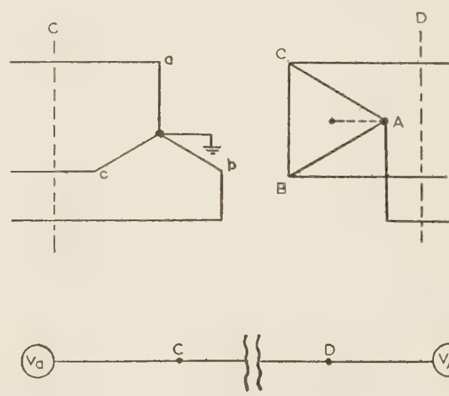


**Fig. 17.**—Vector groups and single line diagrams of star-delta transformer bank.

the faulted transformer may be considered directly. The transformer shown in Fig. 17 will be considered faulted at the points C and D. The equivalent $\alpha$, $\beta$ and 0 component impedance networks are shown in Fig. 18.

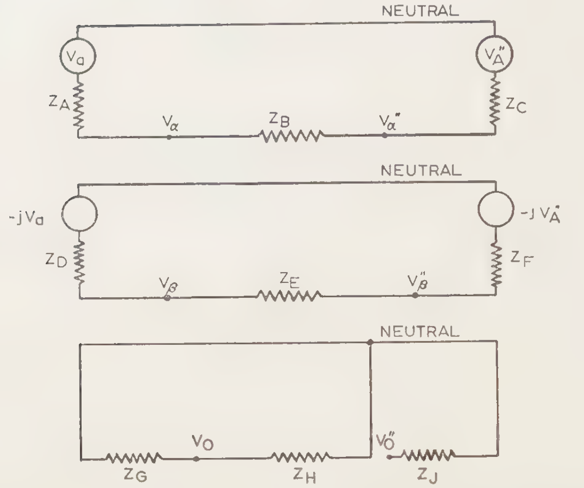


**Fig. 18.**—$\alpha$, $\beta$ and 0 component equivalent circuit of star-delta transformer bank fed by two generating sources.

**(9.1.1) Line-to-Earth Faults at C and D on Conductors *a* and *A*.**

(9.1.1.1) *Application of Stigant's Rule.*

The constraints to be met at C and D are as follows:

$$V_\alpha = -V_0;\ I_\beta = 0;\ I_\alpha = 2I_0 \quad . \quad . \quad . \quad . \quad (87)$$

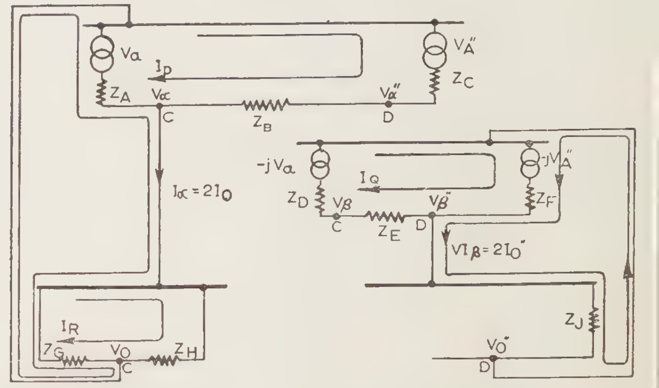


**Fig. 19.**—Connections of $\alpha$, $\beta$ and 0 component networks for line-to-neutral faults on conductor A at D, and on conductor *a* at C with circuit C as a reference circuit.

Replacing $V_\alpha$ and $I_\alpha$ at D by $V''_\beta$ and $I''_\beta$, and $I_\beta$ at D by $-I''_\alpha$ the following relationships are obtained:

$$V''_\beta = V''_0;\ I''_\alpha = 0;\ I''_\beta = 2I''_0 \quad . \quad . \quad . \quad . \quad (88)$$

The equivalent interconnected network satisfying these constraints is shown in Fig. 19. The fault-impedance matrix may be written down by inspection, giving

$Z'' =$ . . . . (89)

| | 0 | 0'' | P | Q | R |
|---|---|---|---|---|---|
| | $Z_A + Z_G/4$ | 0 | $-Z_A$ | 0 | $-Z_G/2$ |
| | 0 | $Z_F + Z_J/4$ | 0 | $Z_F$ | 0 |
| | $-Z_A$ | 0 | $Z_A + Z_B + Z_C$ | 0 | 0 |
| | 0 | $Z_F$ | 0 | $Z_D + Z_E + Z_F$ | 0 |
| | $-Z_G/2$ | 0 | 0 | 0 | $Z_G + Z_H$ |

(9.1.1.2) *Kron Constraint Approach.*

The equivalent network for applied symmetrical faults at C and D is given in Fig. 20. The symmetrical fault-impedance matrix is consequently

$Z' =$ . (90)

| | $C_\alpha$ | $D_\alpha$ | $C_\beta$ | $D_\beta$ | $O$ | $O''$ | $P$ | $Q$ | $R$ |
|---|---|---|---|---|---|---|---|---|---|
| $C_\alpha$ | $Z_A$ | 0 | 0 | 0 | 0 | 0 | $-Z_A$ | 0 | 0 |
| $D_\alpha$ | 0 | $Z_C$ | 0 | 0 | 0 | 0 | $+Z_C$ | 0 | 0 |
| $C_\beta$ | 0 | 0 | $Z_D$ | 0 | 0 | 0 | 0 | $-Z_D$ | 0 |
| $D_\beta$ | 0 | 0 | 0 | $Z_F$ | 0 | 0 | 0 | $Z_F$ | 0 |
| $O$ | 0 | 0 | 0 | 0 | $Z_G$ | 0 | 0 | 0 | $-Z_G$ |
| $O''$ | 0 | 0 | 0 | 0 | 0 | $Z_J$ | 0 | 0 | 0 |
| $P$ | $-Z_A$ | $Z_C$ | 0 | 0 | 0 | 0 | $Z_A + Z_B + Z_C$ | 0 | 0 |
| $Q$ | 0 | 0 | $-Z_D$ | $Z_F$ | 0 | 0 | 0 | $Z_D + Z_E + Z_F$ | 0 |
| $R$ | 0 | 0 | 0 | 0 | $-Z_G$ | 0 | 0 | 0 | $Z_G + Z_H$ |

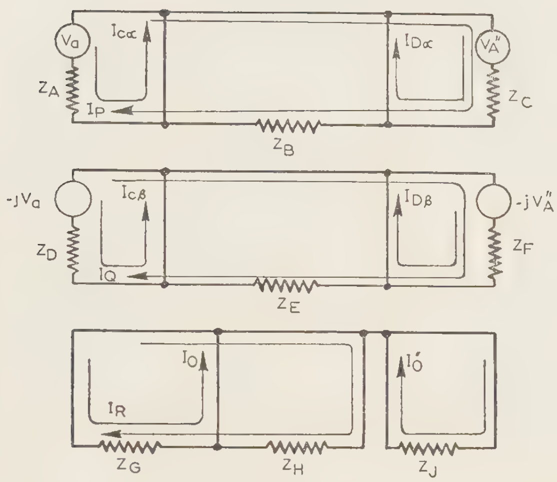


**Fig. 20.**—$\alpha$, $\beta$ and 0 component equivalent circuit with symmetrical faults applied at C and D.

Analysing in terms of $I_0$ and $I_{0''}$, the constraint matrix is given by

$$C = \begin{array}{c|ccccc|} & O & O'' & P & Q & R \\ \hline C_\alpha & 1 & 0 & 0 & 0 & 0 \\ D_\alpha & 0 & 0 & 0 & 0 & 0 \\ C_\beta & 0 & 0 & 0 & 0 & 0 \\ D_\beta & 0 & 1 & 0 & 0 & 0 \\ O & \frac{1}{2} & 0 & 0 & 0 & 0 \\ O'' & 0 & \frac{1}{2} & 0 & 0 & 0 \\ P & 0 & 0 & 1 & 0 & 0 \\ Q & 0 & 0 & 0 & 1 & 0 \\ R & 0 & 0 & 0 & 0 & 1 \\ \hline \end{array} \quad . \quad (91)$$

and the final fault-impedance matrix is given by $Z'' = \bar{C}_t Z' C$. The final voltage-matrix vector becomes $V'' = \bar{C}_t V'$.

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621.311.42:621.316.34

Abstract No. 1919
Dec. 1955

# NEW DESIGN OF CONTROL INSTALLATIONS FOR TRANSMISSION STATIONS

By G. M. MULHERN and D. W. O'NEILL, Graduate.

(Abstract *of a paper read before the* Irish Branch *at* Dublin, 17*th February*, 1955.)

As a portion of its post-war expansion programme the Electricity Supply Board (E.S.B.) constructed a series of 110/38 kV transmission stations in the period 1948–52. As far as possible the stations were built to a common basic plan, but they were not identical. They varied in power-transformer ratings, complexity of control and number of high-voltage outlets, and accordingly their cost varied from roughly £5 to £7 per kilovolt-ampere of installed transformer capacity. Sixteen per cent of gross station expenditure was absorbed by the category of control installations, which embraces all items chargeable to control and supervision, and includes building apportionment, control equipment and cables, protection relays, batteries and pertinent labour.

In 1953, when the planning of another series of transmission stations was undertaken, it was felt that the preceding design of control installations had been unduly expensive. To determine where savings could be obtained most effectively an analysis of control cabling was made. This analysis indicated that control-cable expenditure in the projected new stations could be reduced to one-fifth of that of corresponding previous stations by adoption of the following measures:

For control cables proper, by the use of adequate but minimum copper section and by utilizing suitable plastic insulations and sheathings.

Mr. Mulhern and Mr. O'Neill are with the Electricity Supply Board, Ireland.

Introduction of telephone-type cable for the 24-volt d.c. signalling circuits.

Removal of the protective relays from the control room and repositioning them at their high-voltage cubicles.

Application of common instrumentation, i.e. employing one set of instruments to serve a number of similar high-voltage circuits, measurements being taken by switching the set of instruments into these circuits in turn as desired.

Installation of only single-element indicating instruments on the switchboard.

The implementation of these measures constitutes a new design of control installations which not only saves 80% of the cost of cabling but achieves even more significant economies in control buildings, control equipment and labour. The new design is being applied to five unattended transmission stations at present under construction at Cahir, Galway, Kilkenny, Tralee and Wexford, each of which in its ultimate development will cater for four 110 kV lines, eight 38 kV lines and two 110/38 kV transformers. Some of the main points of difference between the previous and new designs in relation to existing and new stations of approximate similarity in high-voltage layout and magnitude are as follows:

(*a*) The floor area of the control room is reduced from 120 m² in the existing stations to 20·25 m² in the new stations.

(*b*) The cable room in existing stations, which is immediately

beneath the control room and of identical floor area, is replaced in the new stations by a trench behind the panels.

(c) The control room in existing stations has 37 panels, each with double wings to carry ancillaries and wiring. The new control room has seven wingless panels. The walls behind the panels are utilized to carry assemblies of ancillaries consisting of miniature circuit-breakers, fuses, auxiliary relays, subsidiary components and terminal racks. These assemblies are arranged in definite physical relationship with the circuits they govern on the panels.

(d) In existing stations each high-voltage circuit is equipped with a set of conventional indicating instruments. In the new stations only two sets of instruments (ammeter, megawattmeter, megavarmeter and kilovoltmeter) are provided, one for 110 kV lines and the other for 38 kV lines and the 38 kV side of the power transformers. The current coils are rated at 1 amp and are supplied from an auxiliary 5 : 1 current transformer in each high-voltage cubicle. The power instruments are of the single-element type, and hence are accurate only on balanced circuits, but in view of the normal characteristics of E.S.B. transmission systems it is considered that they have precision adequate for their purpose and that such errors as may occur will be tolerable.

In the new control rooms the instrumentation selector keys are positioned in a miniature mimic diagram on the operator's desk. To obtain readings on a particular high-voltage circuit, the appropriate key is thrown, thus operating a contactor in the cubicle, and in consequence the instruments indicate and a lamp lights on the switchboard mimic diagram to identify the circuit being measured.

The contactor in the cubicle connects the instrument transformers to the instrumentation busbars over one make-before-break contact for the auxiliary current transformer and three normal contacts for the voltage transformers. It also has three additional contacts, one being used for the identification lamp and the other two for interlocking. For safety reasons interlocking is necessary to ensure that not more than one contactor can ever be in the closed position simultaneously. The contactor is operated remotely by the selector key acting indirectly through an associated telephone-type plug-in relay.

The plug-in relay is incorporated for the following reasons. First, it offers some flexible maintenance facilities owing to its ease of withdrawal and replacement; among other advantages this aids testing and conveniently allows the disconnection of a high-voltage circuit from the instrumentation scheme while retaining full interlocking and functioning on the remaining circuits. Secondly, it permits telephone-type cable to be used for interconnection with other cubicles and the control room. Thirdly, it simplifies the possible future addition of alternative or supplmentary methods of selector switching, such as local motor-driven cams or perhaps remote operation from a central office for common-instrumentation telemetering.

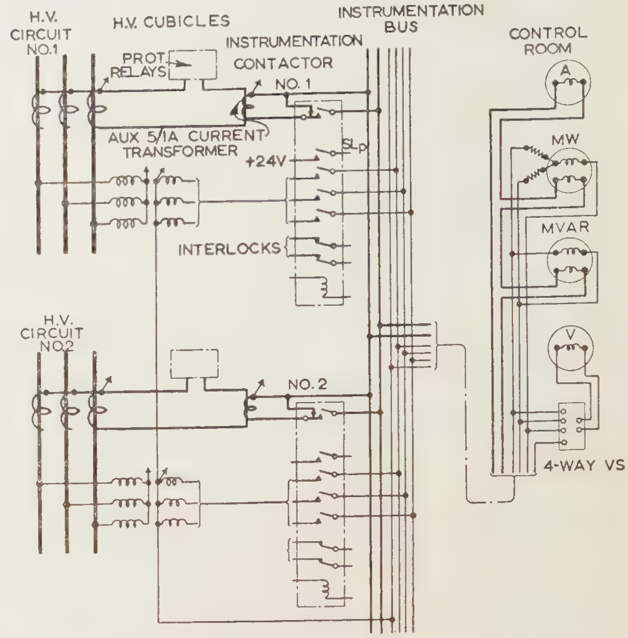


**Fig. 1.**—Diagram of common-instrumentation scheme.

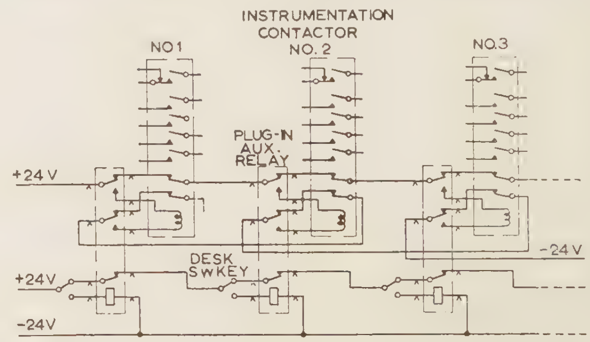


**Fig. 2.**—Interlocking of common-instrumentation scheme.

Fig. 1 is an elementary diagram of the common-instrumentation scheme. Fig. 2 is a schematic of the interlocking circuit design employed. In comparison with the previous arrangements in existing stations, the new design of control installations promises savings of the order of £20 000 per station.

621.384.6

Paper No. 1886
Dec. 1955

# A 20 MeV BETATRON FOR X-RAY THERAPY

By D. MAJOR, B.Sc., B.A., F. R. PERRY, M.Sc.Tech., Member, and K. PHILLIPS, M.Sc., Associate Member.

(*The paper was first received* 16*th February, and in revised form* 4*th May*, 1955.)

SUMMARY

A description is given of a 20 MeV betatron, the first to be installed for X-ray therapy in this country. The machine produces 20 MeV X-rays with an intensity exceeding 100 röntgens/min at 1 m as measured on a condenser thimble chamber surrounded by 6 cm of polystyrene. The betatron magnet can be rotated about its axis through 120°, and together with its suspending framework it can be moved vertically over a range of travel of 7 ft.

After explaining the clinical requirements for such high-energy X-rays, a brief account is given of betatron development and of its principle of operation. A full description of the equipment is then given, followed by an account of its performance and details of its medical application.

## (1) INTRODUCTION

In the treatment of cancer by X-rays it is required to deliver a high dose of ionization at a tumour whilst doing the minimum of harm to the remainder of the body of a patient. The main factors in determining the maximum dose of radiation which can be delivered to a deep-seated tumour are the skin dose received at the surface of the body, and the total amount of radiation absorbed by the whole body. With low-voltage X-rays, the maximum ionization is at the surface of the body and the intensity falls off rapidly with increasing depth. With 20 MeV X-rays, the surface intensity is only 20–30% of the peak value which occurs about 4 cm beneath the skin. This build-up distance corresponds to the mean range of fast electrons, travelling mainly in the forward direction, which are caused by the absorption process of the high-energy X-rays in the body tissue. Beyond this point of maximum ionization the intensity falls off rather more slowly than with lower-energy X-rays. For a given dose at a deep-seated tumour, the total body dose is smaller, giving less risk of damage to healthy tissue, than with low-energy X-rays.

In an orthodox X-ray tube the full accelerating voltage is applied between cathode and anode, but for an energy of 20 MeV this is not practicable. In an electron induction accelerator or betatron the electrons gain energy during a very large number of revolutions round an evacuated toroid, there being a small voltage gain per revolution.

The first successful operation of a betatron was reported in 1941 when Kerst[1] made his first machine of energy 2·3 MeV. A patent on such a machine was filed as early as 1922 by Slepian, and the principles of operation were formulated during the years 1928–29 by others, notably Wideröe.[2] The delay in making a successful machine may be attributed to the stringent conditions under which electrons are accepted into orbits for acceleration in such a machine.

In 1942 Kerst[3] developed a 20 MeV machine. Construction of a machine[4] of similar magnet design was started in 1946. From experience gained on this betatron, a more soundly engineered machine has been developed for 20 MeV X-ray therapy, and this has been installed in a special building provided by the Medical Research Council at the Christie Cancer Hospital and Holt Radium Institute, Manchester.

Previous publications in this country have described betatrons and synchrotrons which had rather low and inconsistent X-ray yields, e.g. Bosley *et al.*,[4] Goward *et al.*[5] and Fry *et al.*[6] This seems to be one of the main reasons why radiologists have been rather slow in this country to accept the betatron as a useful source of high-energy X-rays. The first therapeutic application of a betatron was made by Quastler *et al.*,[7] at the University of Illinois in 1949, and mention must be made of the considerable amount of work which has since been done by the group under Johns,[8] at the University of Saskatchewan, Canada.

With the X-ray output of the machine described in the present paper the treatment time is approximately 5 min. The optimum treatment time seems to be approximately 3–5 min, and little is gained in much higher dose rates by which the treatment time could be reduced to a matter of seconds. In fact, general opinion tends to oppose the idea of very short treatment times owing to the greater danger of causing irreparable damage to the patient due to errors in estimation of the dose rate.

The apparatus consists of an 8-ton magnet with facilities for rotating and lifting. Between the poles of the magnet is a toroidal vacuum chamber which is continuously pumped to a pressure of a few millimicrons of mercury. Electrons are injected into this toroid and accelerated by magnetic induction, and at any desired energy up to 20 MeV they may be caused to strike a target inside the chamber and produce a pulse of X-rays. The X-ray beam forms a narrow cone whose centre line is the direction of motion of the electrons at the moment of hitting the target.

## (2) PRINCIPLE OF OPERATION

In a betatron use is made of one quarter-cycle of an alternating magnetic field. Electrons are accelerated in an evacuated toroidal chamber between the poles of the magnet and they are injected at an energy corresponding to a low magnetic field, which bends them on circular orbits round the toroid. A cross-section of the poles and vacuum toroid is shown in Fig. 1, which

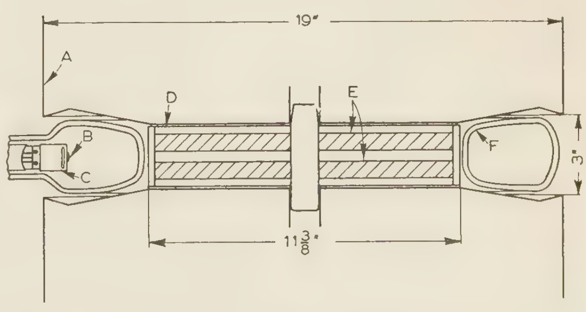


**Fig. 1.**—Cross-section of centre of magnet showing accelerating chamber (cross-section) and electron gun.

A. Top pole of magnet.
B. Platinum target.
C. Electron gun.
D. Centre piece.
E. Steel laminations.
F. Vacuum or doughnut.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
The authors are with Metropolitan-Vickers Electrical Co. Ltd.

indicates the relatively small space occupied by the electron orbits. As the magnetic flux through an electron orbit increases through the magnet cycle, the electron experiences a tangential force, and its gain in energy per revolution in electron volts is equal to the voltage that would be induced in a loop of wire placed at the orbit position. As the electron gains energy by induction, the magnetic guide field at the orbit increases at a suitable rate. To keep the electron on a constant radius from injection to peak energy requires the "Wideröe flux condition," which is that the rate of change of magnetic field at the orbit is equal to half the rate of change of the mean flux per unit area through the orbit. At peak energy, or earlier if desired, the electrons are caused to move away from their equilibrium orbit and strike a target inside the vacuum chamber thus producing X-rays of corresponding energy. The output of the machine consists of short pulses of radiation whose repetition rate is the frequency of the magnet excitation.

Whilst the electrons are being accelerated they travel a very large distance, and in order to allow for small deflections caused by gas scattering, electrostatic repulsion or magnet inhomogeneities, it is necessary for focusing forces to act on the electrons. This is done automatically, both radially and axially, by a magnetic guide field $H$ which decreases with the radius and in such a way that

$$d(\log H)/d(\log r) = -n \text{ where } 0 < n < 1 \text{ (Ref. 9)}$$

The acceptance of electrons into orbits for acceleration presents considerable difficulties. An electron gun projecting into the vacuum chamber injects electrons in a direction approximately tangential to the orbit, and they undergo radial betatron oscillations at angular velocity $\omega\sqrt{(1-n)}$ round the equilibrium path, $\omega$ being the angular velocity round the toroid and $n$ the field index. After a number of revolutions, these oscillations must cause the electrons to come within a small distance of their origin and so strike the electron gun. To avoid this, there must be some mechanism which quickly damps down these oscillations, but explanations of this mechanism by Kerst and others have not been quantitatively satisfactory. A theory has been presented by Barden[10] which appears more likely to explain the cause. There is a portion of the orbit immediately in front of the electron gun in which the space-charge density is high, and this has the same effect on electron radial motion as a local increase in field index $n$. This causes a precession of the electron oscillation together with a damping of its amplitude. If the perturbing effect lasts too long, the oscillation builds up again catastrophically, so the right moment for injection is just before there is a rapid drop in space charge due to termination of the voltage pulse, and this has been confirmed experimentally.

## (3) DESCRIPTION OF THE EQUIPMENT

### (3.1) Magnet Design

The magnet was designed to allow for the possibility of future conversion of the machine into a 50 MeV synchrotron, and the return yoke and side limbs in its present form are run at comparatively low flux-density. These parts of the magnetic circuit are each built up from 17 packets of laminations with $\frac{1}{8}$ in air-gaps between packets. Each packet is a solid unit consisting of 0·014 in steel laminations enamelled and fastened together with a thermosetting adhesive. The pole pieces are built up from radial sectors of laminations to give the particular profile required, which is that the field index $n$ should be just less than 0·75. To satisfy the flux-field relation, additional central flux is produced by a centre-piece between the central flats of the pole pieces. This centre-piece contains two laminated discs of steel, whose thickness and separation determine the stable orbit of the machine. The remainder of the centre-piece is built up from Bakelite, with spiral slots on the surfaces in contact with the steel. A compressed-air supply is brought through the upper pole piece of the machine to cool this centre-piece which operates under conditions of very high flux-density. The poles and return yoke are air-cooled by a system of ducting with two 10 in fans on each horizontal yoke. Air is drawn in through the poles and side limbs in the window of the magnet, and it is controlled in its direction of flow by the spacers between the packets of laminations until it is drawn out by the extractor fans (see Fig. 2).

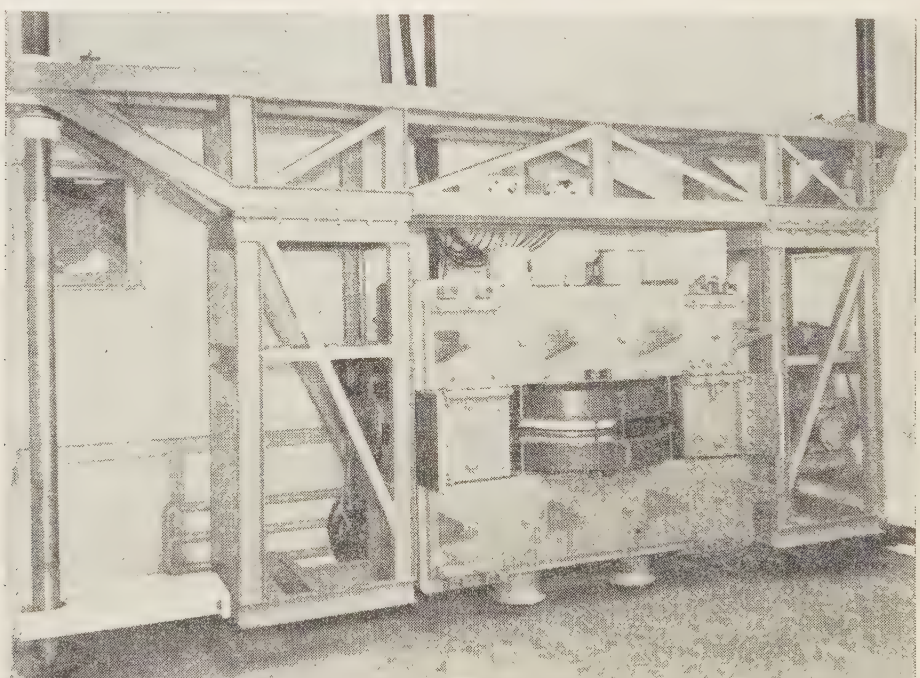

**Fig. 2.**—Magnet under construction mounted in framework showing four cooling fans above and below the magnet.

The energy dissipated in the magnet is about 12 kW, but the cooling allows an 8-hour day to be worked on the treatment duty cycle. Measurements were made on the magnetic field to check azimuthal variation of the axial component of field round the pole, and also to check out-of-phase field variation. The magnet pole separation corresponding to an equilibrium electron orbit of 19 cm was found by using a specially constructed system of concentric coils mounted very accurately in grooves machined in a thick Bakelite ring which fitted round the centre piece in the median plane of the magnet. A voltage due to the rate of change of flux through a single coil of 19 cm radius was opposed to a voltage corresponding to the rate of change of guide field through a multi-turn coil forming an annular ring. The number of area turns of this coil was arranged so that the induced voltage equalled that in the flux coil when the flux-field relation was satisfied. The voltage minimum gave the orbit position accurately to within 1 mm.

## (3.2) Excitation of the Magnet

For an electron energy of 20 MeV, a peak magnetic field of approximately 3 600 gauss is required at the 19 cm orbit radius. The corresponding reactive power required by the energizing coils is 14 kV 106 amp (r.m.s.) at 150 c/s. The magnet coils are tuned to resonate with a parallel capacitor bank of capacitance 8·2 $\mu$F at a frequency three times that of the mains supply. The bank of capacitors is made up of two halves in series, each half consisting of seven units rated at 2·23 $\mu$F, 7·07 kV and a set of trimming capacitors of 2·23 $\mu$F, 1·115 $\mu$F, 0·558 $\mu$F, 0·372 $\mu$F and 0·186 $\mu$F, all rated at 7·07 kV. This allows the magnet to be tuned over a wide range of frequency variation, and the machine can be run at a mains supply frequency as low as 47 c/s. Frequencies of 48 c/s or worse were not infrequent when this design point was considered. The tuning is effected by switching in suitable trimming capacitors by mercury switches, which are operated by solenoids, switched from the control rack. The mercury switches are insulated for 7 kV (r.m.s.) but are not intended to be operated with the magnet energized. The tuning capacitors are housed in a basement room some considerable distance from the other equipment. This is not likely to cause any inconvenience since they require very little maintenance and attention.

The reactive power in the tuned circuit is nearly 1 500 kVA, and the power required to maintain the oscillations by supplying losses in the magnet and capacitor bank is about 15 kW. This power is fed into two parallel windings in the same coil boxes as the main exciting coils, each winding taking approximately 580 volts 13 amp at 150 c/s. This 150 c/s voltage is supplied from a continuously-variable auto-transformer across the output of a special tripling transformer (see Fig. 3) which has a star primary, and an open-delta secondary winding, with the core at very high flux density. Owing to the high leakage inductance associated with a nearly saturated core, both primary and secondary circuits require power-factor correction, the former for the 50 c/s supply and the latter for the 150 c/s component.

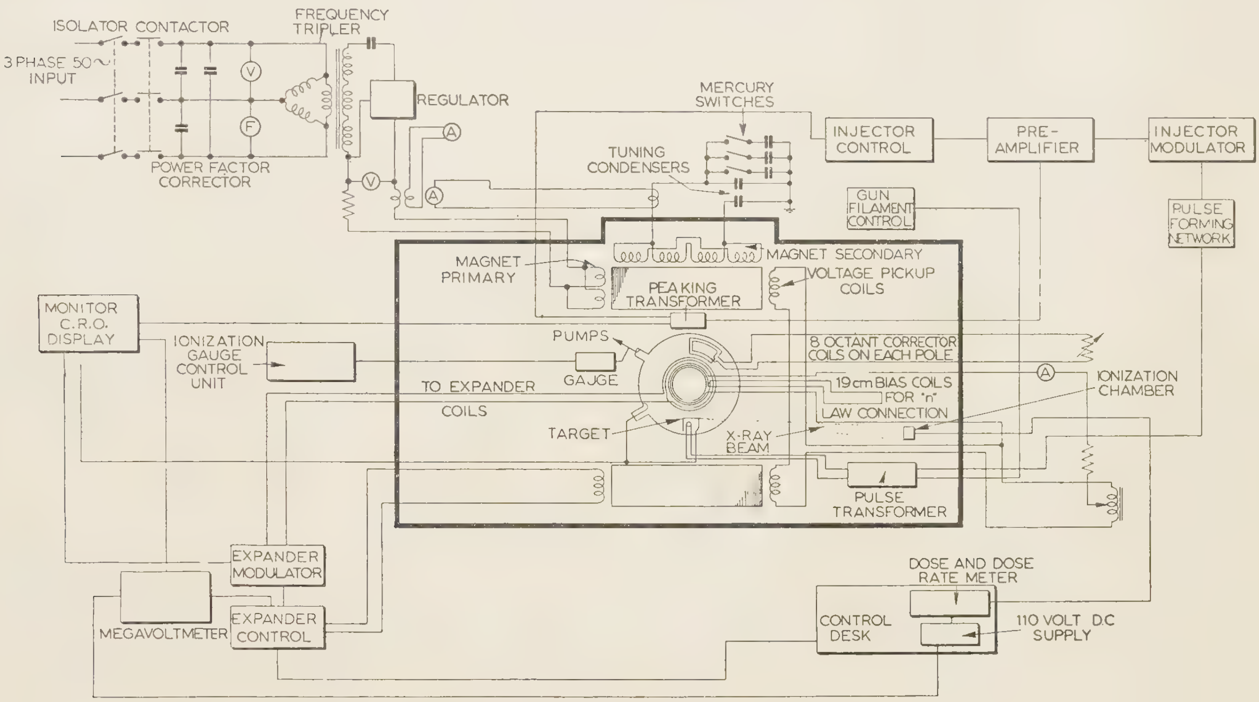


**Fig. 3.**—Block schematic of connections.
The shaded enclosure represents the limits of the treatment room.

## (3.3) The Electron Gun and the Accelerating Chamber

The most important requirements of the electron gun for use in the betatron are that:

(*a*) It should be physically small so as not to intercept any of the circulating beam after the first few electron revolutions.
(*b*) It should be able to withstand high pulsed voltages, since the X-ray yield increases with injection voltage.
(*c*) It should also have good electron optics and a cathode giving a high peak emission.

The gun itself is shown in Fig. 4 and was designed for insertion through a radial arm of the doughnut. It is a simple triode structure with a 0·008 in-thick tungsten spiral filament, wound on a 0·020 in-diameter mandrel and housed in a molybdenum focusing cup. The anode is earthed and completely encloses the filament and cup, except for a narrow slit through which the

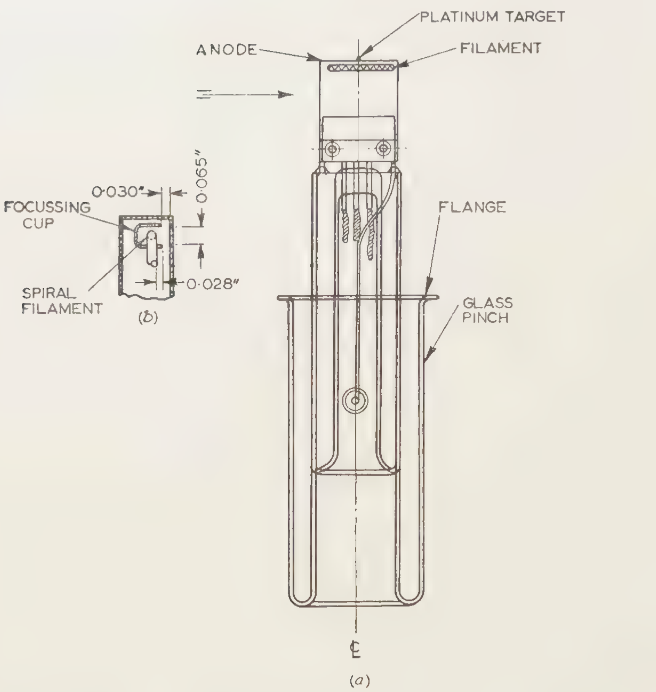


Fig. 4.—Betatron electron gun.

(a) General arrangement.
(The electode structure is mounted on a flanged glass pinch to ensure accurate positioning of the gun in the doughnut.)
(b) Part section on the centre of electrode structure viewed in direction of arrow shown in (a).

electrons are fired. Under test conditions a similar gun has withstood 4 microsec impulses of over 100 kV and has been used successfully at 75 kV peak in a betatron. Voltage gradients of approximately $10^6$ volts/cm exist in certain parts of the electrode structure. These high gradients have been attainable only by careful cleaning and electrolytic polishing of the electrodes. In order to obtain good electron optics, the electrode structure has to line up accurately to within 0·001 in. The high peak emission current (650 mA) and long life have been attained by careful annealing of the filament after it has been welded into position on to the glass pinch. The normal filament current is approximately 4·5 amp for a peak emission of about 500 mA.

The gun is completely demountable, and when the filament burns out it is only a matter of a few hours' work to replace it. The X-ray target is a platinum block welded on to the extremity of the anode.

The accelerating toroid is made of hard glass and is approximately 19 in outside by 11$\frac{5}{8}$ in inside diameter with a nominal wall thickness of $\frac{3}{16}$ in. Four flanged side ports are fixed to the main body of the toroid (see Fig. 5). One port is used for evacuation of air and another for the electron gun; the two remaining ports can be used for separate targets as required. The inside of the doughnut is coated with a thin layer of palladium which is connected to earth. The thickness of the coating is based on a compromise such that its resistance has to be low enough to conduct away rapidly any stray charges which build up on the inside walls and yet high enough to minimize any eddy currents in itself produced by the changing magnetic field. An overall resistivity of about 20–80 ohms per square was found to be satisfactory. Other important requirements of the coating are that it should be completely continuous and physically hard. Small bare patches on the coating are likely to charge up and deflect the electron beam. In order to avoid any of these discontinuities, it was found advisable to roughen the inside surface

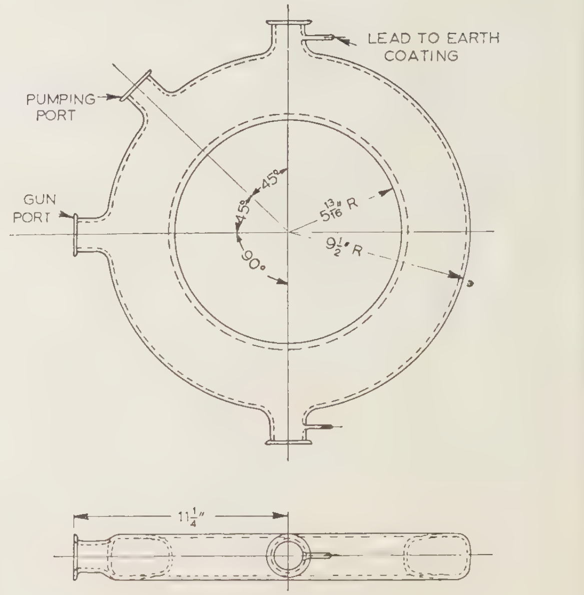


Fig. 5.—Betatron doughnut.
Two spare ports are blanked off and not utilized with the betatron used for therapy.

prior to application of the palladium solution. This method guaranteed a more evenly distributed film and prevented any undesirable patches on the inner walls. There has not been sufficient running time to give an accurate figure for coating life, but it is known to be more than 500 hours.

### (3.4) The Pumping Plant

For efficient working of the betatron it is essential to maintain a pressure of less than $5 \times 10^{-6}$ mm Hg in the doughnut. The decision to use a continuously-evacuated doughnut was based on previous experience with the more conventional high-voltage X-ray tubes and on the radiologist's attitude to completely sealed-off systems. It has been found, over a considerable number of years, that continuously evacuated systems have caused so little trouble that sealed-off tubes are almost eliminated on purely economic grounds unless they can be produced at a very low price.

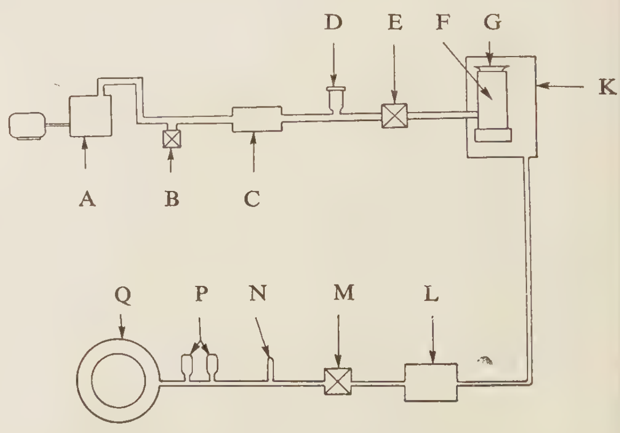


Fig. 6.—Schematic of pumping equipment.

A. Mechanical rotary pump.
B. Air leak.
C. $P_2O_5$ trap.
D. Pirani gauge.
E. Backing-side valve.
F. Diffusion pump.
G. Water-cooled baffle.
K. Steel tank.
L. Cold trap.
M. Fineside valve.
N. Discharge tube.
P. Ionization gauges.
Q. Doughnut.

When a gun filament burns out, in the case of a continuously-evacuated doughnut a spare gun can easily be fitted, but approximately 6 hours are required to re-evacuate to a suitable working pressure. A sealed-off doughnut can be changed with very little loss in working time. Repair of the gun, however, is more expensive in the latter case and in practice the doughnut has to be returned to the manufacturer. On the other hand, demountable guns can be repaired by a technician at the hospital. The pumping plant consists of a 4 in oil-diffusion pump backed by a mechanical rotary pump. The pumping speed measured just above the diffusion pump is about 100 litres/sec. A schematic of the complete plant is shown in Fig. 6. The plant is semi-automatic and protects itself against large leaks and failure of cooling water and mains supply. The major problem which had to be overcome with the plant was concerned with the rotation of the betatron. This meant that the high-vacuum line to the doughnut had to be rotated, but it was impossible to incline the oil-diffusion pump through the desired angle. The difficulty was overcome by suspending the pump F vertically in a cylindrical steel tank K pivoted on the centre line of rotation of the betatron

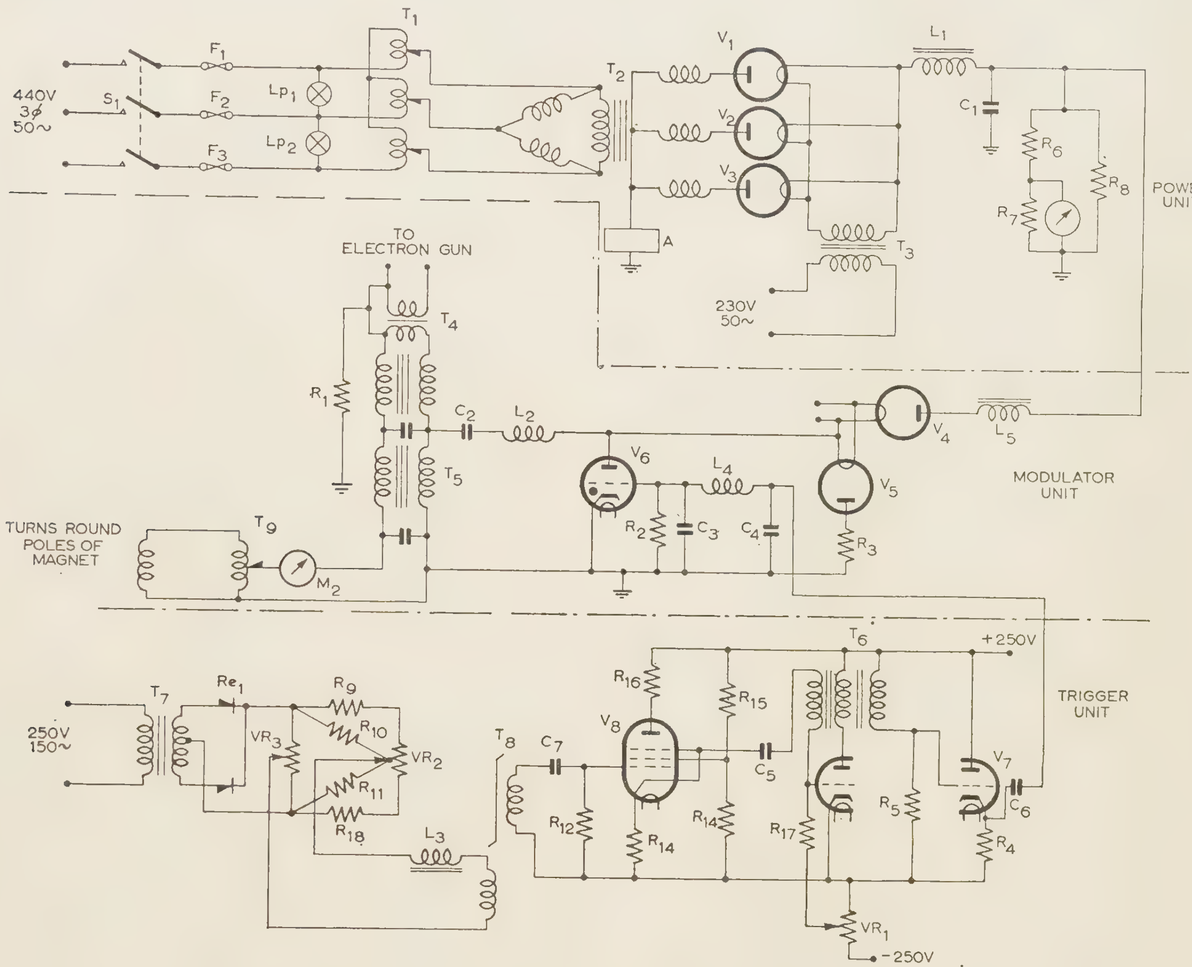


**Fig. 7.**—Circuit diagram of modulator and trigger units.

Component values

| Resistors | | Capacitors | | |
|---|---|---|---|---|
| $R_1$ | 7·5 kΩ. | $C_1$ | 0·25 μF. | 14 kV. |
| $R_2$ | 47 kΩ. | $C_2$ | 0·025 μF. | 10 kV. |
| $R_3$ | 2 kΩ. | $C_3$ | 220 μμF. | 350 volts. |
| $R_4$ | 10 kΩ. | $C_4$ | 220 μμF. | 350 volts. |
| $R_5$ | 47 kΩ. | $C_5$ | 220 μμF. | 350 volts. |
| $R_6$ | 70 MΩ. | $C_6$ | 0·05 μF. | 350 volts. |
| $R_7$ | 100 Ω. | $C_7$ | 0·01 μF. | 350 volts. |
| $R_8$ | 10 MΩ. | | | |
| $R_9$ | 150 Ω. | | | |
| $R_{10}$ | 22 Ω. | | | |
| $R_{11}$ | 22 Ω. | | | |
| $R_{12}$ | 47 kΩ. | | | |
| $R_{13}$ | 220 Ω. | Valves | | |
| $R_{14}$ | 47 kΩ. | V1 | | |
| $R_{15}$ | 47 kΩ. | V2 | | |
| $R_{16}$ | 220 kΩ. | V3 | 19H5. | |
| $R_{17}$ | 22 kΩ. | V4 | | |
| $R_{18}$ | 150 Ω. | V5 | | |
| $VR_1$ | 50 kΩ. | V6 | BT83. | |
| $VR_2$ | 5 kΩ. | V7 | ECC33. | |
| $VR_3$ | 50 Ω. | V8 | 6F14. | |

Transformers

| | Winding | Description |
|---|---|---|
| T1 | Auto | 230 volts, 2·5 amp, type 200 CUH.36. |
| T2 | Primary | 400 volts, 3-phase, delta wound. |
| | Secondary | 10 kV, zig-zag wound 1 000 VA. |
| T3 | Primary | 230 volts, 50 amp (r.m.s.). |
| | Secondary | 4 volts, 12 amp. |
| T4 | | 4 : 1 step-down current transformer. |
| T5 | | Bifilar pulse transformer 9 : 1. Step-up, 100 kV, 4 microsec. |
| T6 | | Blocking-oscillator pulse transformer. |
| T7 | Primary | 250 volts, 150 amp. |
| | Secondary | 10–0–10 volts, 1 amp. |
| T8 | | Peaking strip. |

Miscellaneous

| | |
|---|---|
| S1 | 3-pole, 10 amp switch. |
| Re1 | Rectifier type V 45–1–12. S.T.C. |
| $L_1$ | 100 H, 45 mA, d.c. choke. |
| $L_2$ | 50 μH, 10 kV insulation choke. |
| $L_3$ | 0·2 H, 150 mA (d.c.), choke. |
| $L_4$ | 250 μH, r.f. choke. |
| $L_5$ | 300 H, 30 mA d.c. choke. |
| F1, 2, 3 | Fuse, 5 amp. |
| Lp1, 2 | Signal lamp, 440 volts working. |
| A | Relay type 3000. 6 500-ohm coil. Two change-over contacts. |
| M1 | Meter 0–100 amp. |
| M2 | Meter 0–1 amp. |

magnet. This meant that the tank rotated about the diffusion pump and eliminated the need for any form of rotating seal in the low-pressure line to the doughnut. (The method was proposed by Mr. P. P. Starling.) The only rotating seal required was on the higher-pressure backing-side line to the rotary pump. A baffle, G, was mounted above the diffusion pump to prevent any of the oil vapour from escaping into the tank and eventually being cracked on the high-temperature pump heater. As a further deterrent to the diffusion of any oil vapour into the doughnut, a solid-carbon-dioxide trap L is included between the tank and the doughnut.

The procedure for switching on the vacuum system consists simply of starting the rotary pump A, whereupon the backing-side valve E opens automatically after a short delay. When the backing pressure has been reduced to about $4 \times 10^{-2}$ mm Hg, a relay, operated by a thyratron from a Pirani gauge D, closes contacts in the circuit of the oil-diffusion pump heater. The heater may then be switched on by the hand operation of a push button which also opens the fine-side valve M. If any failure of the mains supply occurs, the system automatically protects itself by closing the fine- and backing-side valves, thus cutting off the doughnut Q and tank from the rotary pump. An automatic air leak B is provided on the rotary pump to prevent any of its oil being sucked into the backing line. A cooling-water failure switches off the diffusion-pump heater. The pressure inside the doughnut is measured by means of an ionization gauge P mounted on the vacuum tubing between the fine-side valve and the doughnut. The ionization current is measured by means of a double-triode electrometer circuit. Provision is also made for the protection of the gauge and gun filaments in case of a vacuum failure. In order to facilitate continuous running of the betatron, the pumping equipment is normally left running overnight.

### (3.5) Electronic Equipment

In order to inject the low-energy electrons into the doughnut, the gun is modulated with a 4 microsec half-sine-wave pulse, 150 times per second. The circuit for providing this pulse is shown in Fig. 7, and consists mainly of a variable 0–10 kV d.c. power unit, which is supplied from the 3-phase 50 c/s mains, and a modulator unit. A hydrogen-thyratron switch V6 is used to discharge a $0 \cdot 025\,\mu F$ capacitor $C_2$ through a $50\,\mu H$ inductance $L_2$, and the primary of a 1 : 9 bifilar pulse transformer T5, across the secondary winding of which is connected a non-inductive resistor $R_1$ of 7 500 ohms. The pulse transformer is mounted on the back of the betatron magnet and connected to the gun by means of a length of high-voltage polythene cable. The filament supply to the gun is taken via a Variac transformer from a coil of several turns wound round the side limb of the magnet. The impulse voltage applied to the gun can be varied from 5 kV (peak) to 80 kV (peak) by suitable adjustment of the 3-phase Variac on the transformer in the d.c. set. The time of firing of the thyratron switch is controlled to better than 0·1 microsec, by means of a peaking strip situated near the main gap of the betatron. The peaking strip is simply a piece of 0·002 in thick × 2 in long Permalloy upon which is wound a 100-turn coil. The strip produces a 10 microsec 20-volt pulse, which is then sharpened by a blocking oscillator. The actual time of firing of the peaking strip is controlled by means of a second 100-turn winding supplied from a d.c. rectifier set which produces the bias field necessary to move the peaking strip pulse up to a maximum of 15 microsec from the time of zero field. The timing adjustment is necessary so that, when electrons of a particular initial energy are injected, the magnetic guide field is of the correct magnitude for them to circulate round the doughnut.

When the electrons have been successfully injected on to a stable orbit and have gained sufficient energy, it is necessary to expand the orbit so that they strike a target of high-atomic-number material. This is accomplished by means of another modulator which produces a 4 microsec half-sine pulse of approximately 200 amp (peak) in two single-turn coils in series, one above and one below the doughnut. The circuit is shown in Fig. 8. A $0 \cdot 125\,\mu F$ capacitor $C_6$ is charged to 3·5 kV via a

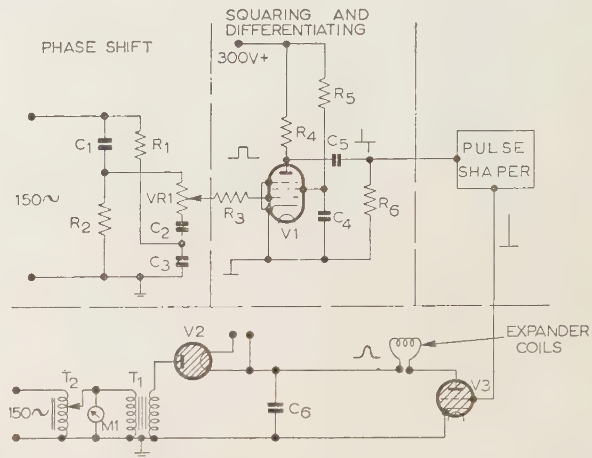


**Fig. 8.**—Circuit diagram of expander modulator.

Component values

| Resistors | Capacitors |
|---|---|
| $R_1$ 24 kΩ. | $C_1$ 0·06 μF, 500 volts (working). |
| $R_2$ 24 kΩ. | $C_2$ 0·06 μF, 500 volts (working). |
| $R_3$ 1 MΩ. | $C_3$ 0·005 μF, 350 volts (working). |
| $R_4$ 22 kΩ. | $C_4$ 1·0 μF, 600 volts (working). |
| $R_5$ 100 kΩ. | $C_5$ 0·001 μF, 1 kV (working). |
| $R_6$ 47 kΩ. | $C_6$ 0·125 μF, 3 kV (working). |
| $VR_1$ 250 kΩ. | |

Valves
V1 6SH7.
V2 RG3–250.
V3 BT83.

mercury diode V2, and discharged 150 times per second by means of a hydrogen-thyratron switch V3. The time in the acceleration cycle, at which the expander fires, controls the energy of the expanded electrons. This time is governed by a simple adjustable timing circuit (see Fig. 8). A 150 c/s reference voltage from two turns round the side limb of the magnet is fed to an *RC* phase-shifter and thence to a squaring and differentiating circuit. The resulting positive pulse is shaped and used to fire the expander modulator. By adjusting the potentiometer $VR_1$, it is possible to vary the energy of the electron beam at expansion up to 20 MeV to within a known accuracy of ±0·25 MeV. The energy of the expanded electrons is indicated by means of a megavoltmeter, which consists of a simple thyratron integrator similar to the one described by Westendorp.[11] This energy control is not normally necessary in radiology work although there seems to be some doubt as to the optimum energy of X-rays required to treat various types of tumours. Also, if future research work indicates possibilities for electron therapy, it would then be desirable to vary the electron energy so that the electron range in the body tissue was equal to the distance of the tumour below the surface skin.

In order to adjust the machine initially and also to give evidence of the performance of the various circuits, a fast cathode-ray-oscillograph monitoring unit was provided, consisting of two cathode-ray tubes. One cathode-ray tube has a triggered time-base with a length of approximately 10 microsec and provision is made for displaying the injector and expander pulses and also the voltage across a non-inductive 100-ohm resistor in the earth lead from the doughnut coating. This

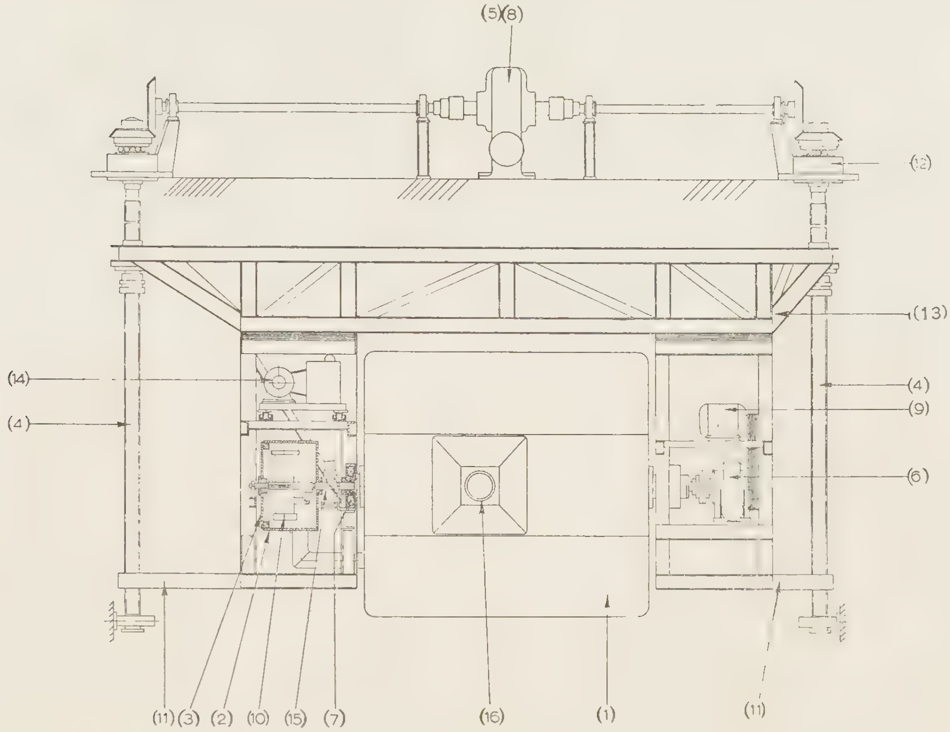


**Fig. 9.**—Elevation of magnet and framework showing controls for raising and tilting.

(1) Betatron magnet.
(2) Vacuum tank.
(3) Rotating seal.
(4) Lifting lead screw.
(5) Gear box for vertical motion.
(6) Gear box for rotary motion.
(7) Main bearing.
(8) Horizontal shaft and bevel-gear assembly.
(9) Motor drive for rotary motion.
(10) Diffusion pump.
(11) Guides.
(12) Thrust bearing.
(13) Cantilever framework.
(14) Rotary backing pump.
(15) Vacuum line to rotary pump.
(16) Collimator.

doughnut current display is used as a guide to injection timing and electron-gun emission and for revealing any fault conditions at injection. The other tube has a circular time-base indicating the relative times of firing of the injector and expander thyratrons.

### (3.6) The Positioning Mechanism

The underlying principle that governed the design of positioning mechanism for the betatron was the fact that it was undesirable to treat a patient in an awkward and uncomfortable position. In order to make it possible to treat any part of a recumbent patient with the X-ray beam entering the body from any angle, the magnet had to be rotatable about an axis perpendicular to the X-ray beam and through an arc ranging from 15° above the horizontal plane to 15° past the vertical, i.e. a total angular sweep of 120°. Provision for raising the machine vertically through a total distance of 7 ft was also made. These separate motions were accomplished by mounting the magnet in an inverted U-shaped cantilever framework (see Fig. 9). The upper corners are suspended on two 6 in-diameter phosphor-bronze nuts moving on two 18 ft vertical steel lead-screws. The lower corners were provided with forked guides which also run on the lead-screw. The lead-screws were driven from above the treatment room by means of a 15 h.p. 3-phase electric motor geared down by a ratio of 20 : 1 to a speed of 70 r.p.m. A horizontal shaft from the gearbox drives the vertical lead-screws by means of two 18 in-diameter bevel-gears.

The power for the rotary motion of the magnet about its axis is delivered by a 3 h.p. motor through a 200 : 1 ratio gearbox. The magnet is mounted on ball-bearing journals. Both driving systems can be controlled from a series of push buttons mounted on a movable pedestal and located in the treatment room, thus enabling the radiographer to adjust the relative position of the patient and the machine accurately; even though the magnet weighs 6 tons it is possible to stop it to within $\frac{1}{8}$ in vertically and circumferentially.

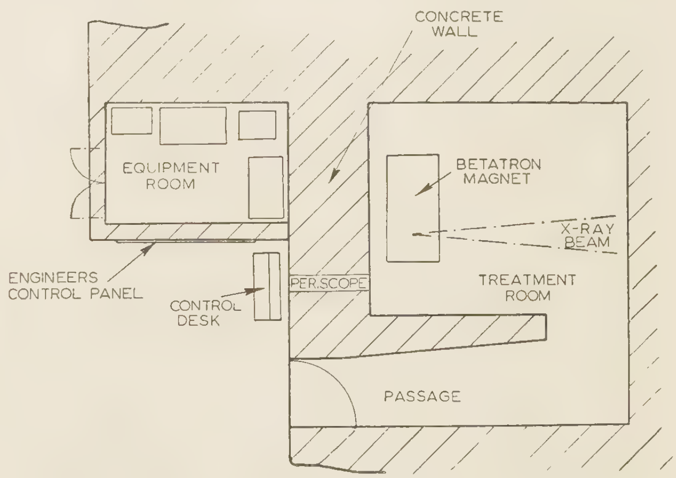


**Fig. 10.**—Plan view of layout of treatment room, equipment room and controls.

### (3.7) General Layout and Control

The layout of the betatron installation is shown in Fig. 10. The machine itself is housed at one end of the treatment room, which is 20 ft long by 16 ft wide. Adjacent to the treatment

room is the equipment room which contains the tripling transformer, regulator and power-factor-correction capacitors. The electronic equipment is contained in four racks built into the wall separating the equipment room and the control hall. The radiographer's control desk is situated in the control hall near the equipment racks. Owing to the large amount of stray radiation which exists when the machine is running, the operators must be protected. In order to ensure this protection, the concrete dividing wall between the control room and treatment room is 3 ft 6 in thick. The front wall into which the X-ray beam is generally fired is 6 ft thick. Entrance to the treatment room is made down a passage which forms an effective trap and prevents any stray radiation from entering the control hall. The patient may be observed from the radiographer's desk by means of a periscope system of mirrors built into the wall. The walls of the treatment room were partly covered with acoustic tiles in an attempt to reduce the loud noise of the betatron to a tolerable level, and with the machine fully excited the noise level was kept below 110 dB. Since short treatment times are required, the noise is not expected to be disturbing to the patient.

The operation of the machine controls is not difficult and is similar to the operation of conventional X-ray equipments. At the start of a day's run, the tripling transformers and filament heaters are switched on. When the operator is ready to produce X-rays, the magnet is energized by adjusting a regulator to obtain the required reading on the megavoltmeter. The operator then turns up the injector filament current and injection voltage to known settings, and adjusts the filament current and timing to obtain the maximum reading on the X-ray output meter. Other control adjustments should not be necessary during normal running.

During early use of the betatron, control is split between an engineer in charge of the control racks and a radiographer sitting at a control desk and responsible for starting the treatment and stopping at a specified total X-ray dose. This is done by a switch controlling the expander circuit, which is operated either by a timer or at a preset dose controlled from the X-ray monitoring circuit.

### (4) MACHINE PERFORMANCE

Wherever possible, in describing how X-ray output varies with a given parameter, the output scale will be given directly in röntgens per minute at 1 m from the target. The usual practice, particularly with machines of low output, has been to quote "relative output," and this is to be avoided, as a particular curve may vary according to whether a machine is working at full output or not.

The method of measuring output has been to calibrate an ionization chamber with a front wall of 6 cm of polystyrene against a standard capacitor thimble chamber surrounded by 6 cm of polystyrene. This is more than the normal thick-wall chamber depth, because all quoted measurements on the betatron were done before the collimator was made. In this case the X-ray beam contains a large number of high-energy electrons scattered out of the doughnut, which give spurious output readings unless absorbed by material of low atomic number. Figures for output using a smaller wall thickness of low-atomic-number material are meaningless, unless it is clear that they refer to a well-collimated beam free from "primary" electrons.

Another method of measuring machine outputs frequently used in America has been to surround the thimble chamber with $\frac{1}{8}$ in thickness of lead and quote the dose measured in this way. Owing to the intensifying action of the high-atomic-number material, this effectively doubles the measured output.

It is difficult to obtain reliable figures for output from betatrons of a similar type in America, and allowance has to be made for the fact that they work at a mains supply frequency of 60 c/s instead of 50 c/s, and measured outputs are quoted for a focus skin distance (f.s.d.) of 3 ft rather than 1 m. Reported outputs, therefore, of 200 röntgens/min at 24 MeV represent a less efficient machine under the conditions in which the 20 MeV betatron described in the paper gives 112 röntgens/min at 1 m.

An important role in obtaining high X-ray outputs is played by two sets of corrector coils built into two pressboard formers shaped to fit the magnet-pole profile. The first form of correction comprises eight coils equal in width to the doughnut and covering 45° in azimuth, each coil consisting of six turns of wire. Corresponding "octant" coils above and below the doughnut are connected in series together with a variable resistor, a fixed resistor and a switch. The induced voltage creates an out-of-phase current in these coils which are used to compensate for unavoidable out-of-phase magnetic fields. From a comparison of corrector-coil settings with measurements of the out-of-phase fields, it appears that the corrector coils are not just neutralizing magnet errors, and it is thought that they introduce a first harmonic in the field which is helpful in the injection process. The other form of correction consists of a coil of radius 19 cm above the doughnut in series with a similar coil below the doughnut. The voltage induced in these coils is fed in series with a fixed resistor and a variable voltage, 180° different in phase, controlled by a Variac fed from coils on a side limb of the magnet. An easily varied correction current lagging or leading the magnetic field is thus obtained, and this current alters the field index, $n$, law of the magnetic field at the time of injection. A lagging current of about 1·5 amp gives a considerable increase in machine efficiency (see Fig. 11). It is thought that the decrease

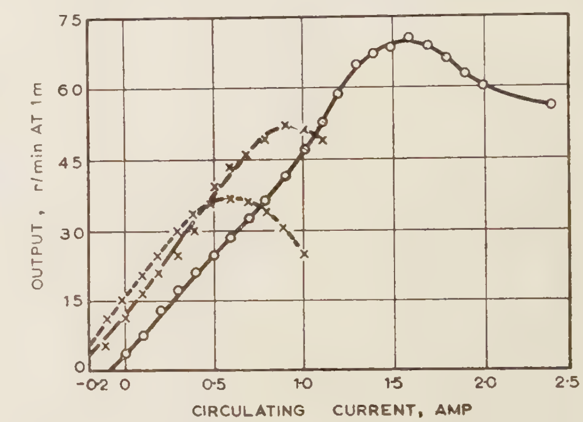


Fig. 11.—Output versus circulating current in orbit coils.
×····× 100 mA emission.
×——× 200 mA emission.
○——○ 400 mA emission.

in $n$ caused by this coil together with the effective increase due to the space charge of the electrons make it equal to three-quarters for the vital portion of the injection process.[10] A coil in this position which is pulsed during the injection process has been described by Adams.[12] The practice of pulsing the coils does not give any benefit in the case of this machine.

The other parameters which can be varied to gain maximum X-ray output are:

(a) Timing of injection.
(b) Betatron energy.
(c) Radial position of electron gun.
(d) Betatron stable-orbit radius.
(e) Injection voltage.
(f) Electron-gun emission.

The various effects of these parameters are considered below.

### (4.1) Timing of Injection

Accurate timing is important, since the acceptance time of the injected electrons is approximately 0·25 microsec, and timing of the pulse is critical to about 0·1 microsec. The correct adjustment of this control is indicated by the X-ray yield reaching a maximum.

### (4.2) Betatron Energy

X-ray output varies as rather more than the third power of the peak electron energy (see Fig. 12).

i.e.
$$\frac{P_2}{P_1} = \left(\frac{W_2}{W_1}\right)^{3\cdot 1}$$

where $P_1$ = X-ray output at energy $W_1$.
$P_2$ = X-ray output at energy $W_2$.

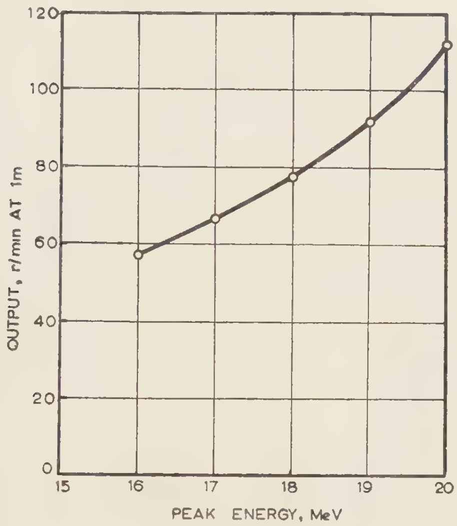


**Fig. 12.**—Output versus peak energy (55-volt injection).

The beam power is linear with energy, but the X-rays become concentrated into a smaller cone with increasing energy.

### (4.3) Electron-Gun Radius

X-ray output increases slowly as the radius of the electron gun is increased from just outside the stable-orbit radius up to a radius just less than that for which the field index becomes equal to unity (see Fig. 13). For larger gun radii the output

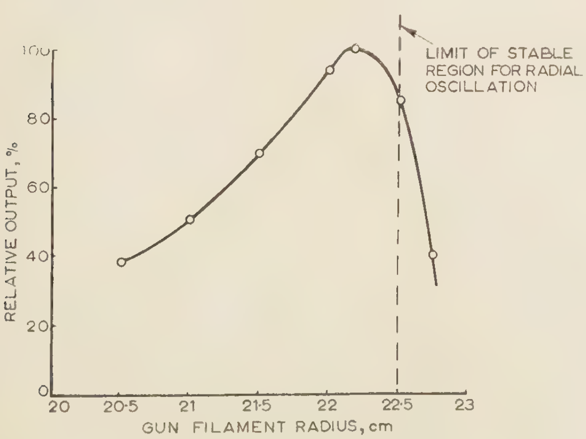


**Fig. 13.**—Output versus gun radius.

drops off very quickly in good agreement with the theory of focusing for radial oscillations.[9]

### (4.4) Betatron Stable-Orbit Radius

With the type of doughnut on which most of the machine experiments have been done, X-ray output is rather critically dependent on the radius of the stable orbit. The cross-section of the doughnut has been changed to give a smaller inner radius and a bigger vertical aperture at the inner radii. This has resulted in an increase in X-ray output of approximately 60% and has made the machine much less sensitive to the stable-orbit radius used. The two sections of doughnut are shown in relation to the magnet in Fig. 14. Included in the figure are the boun-

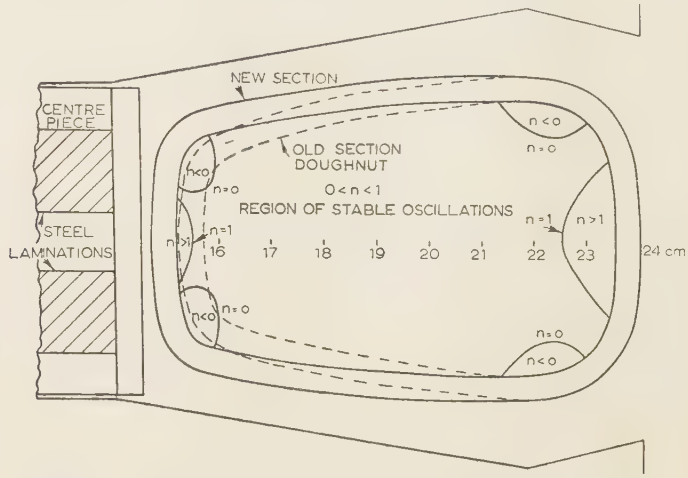


**Fig. 14.**—Cross-sections of new and old doughnuts in relation to magnetic field index $n$.

daries within which magnetic-field variations allow the electrons to perform stable oscillations. The importance of adequate vertical aperture has been found with other machines,[13] and it is probable that the electrons which are accepted for acceleration undergo large oscillations initially, both radially and vertically.

### (4.5) Injection Voltage

X-ray output varies linearly with injection voltage (see Fig. 15) up to the highest voltages so far obtained, about 70 kV (peak), the limit being set by vacuum arc breakdown. Normal running voltages are about 55 kV peak.

### (4.6) Electron-Gun Emission

The required emission for maximum X-ray output increases approximately linearly with injection voltage (see Figs. 15 and 16), and is about 650 mA at 55 kV. For the filament current corresponding to this emission, the gun filament has a normal life in excess of 500 hours.

## (5) MEDICAL APPLICATION

The betatron magnet is carried on a special mounting described earlier, which enables the radiographer to position the direction of the X-ray beam with great accuracy. The machine in a partially raised and tilted position is shown in Fig. 17. The lead shielding used to reduce any stray radiation is covered by means of the steel front panel. A cross-section of this shielding together with the collimator is shown in Fig. 18.

The collimator housing allows for horizontal and vertical displacement and also rotation about a vertical axis (the magnet being positioned for a horizontal X-ray beam). These three

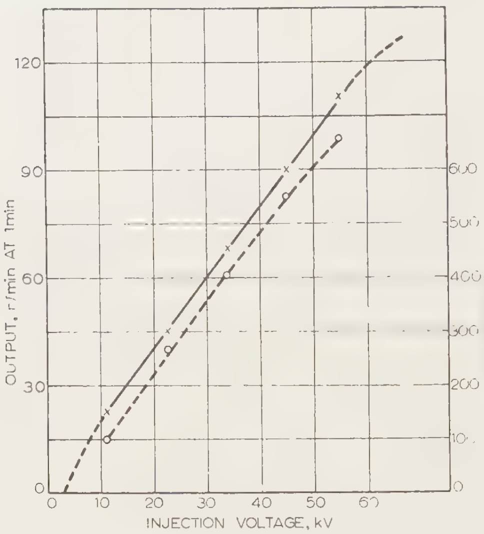


**Fig. 15.**—Output versus injection voltages (20 MeV).
×——× Output.
○——○ Required emission.

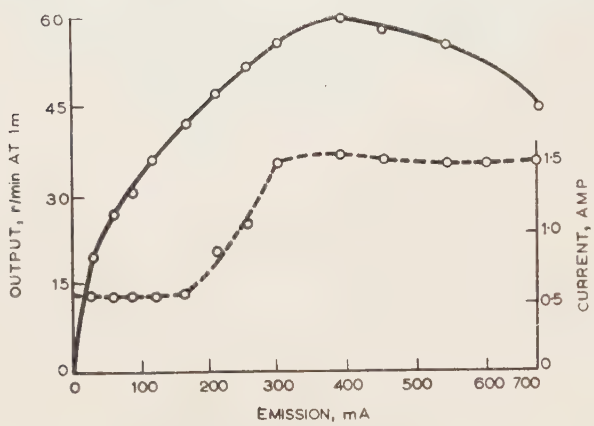


**Fig. 16.**—Output versus emission.
○——○ Output.
○····○ Required circulating current.

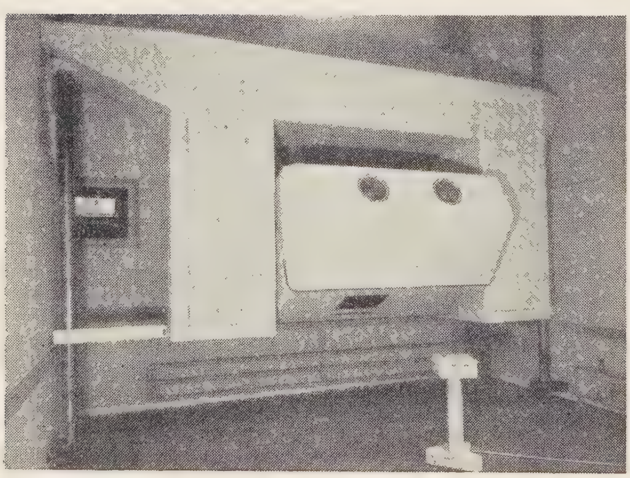

Fig. 17.—View of magnet slightly tilted and partially raised.

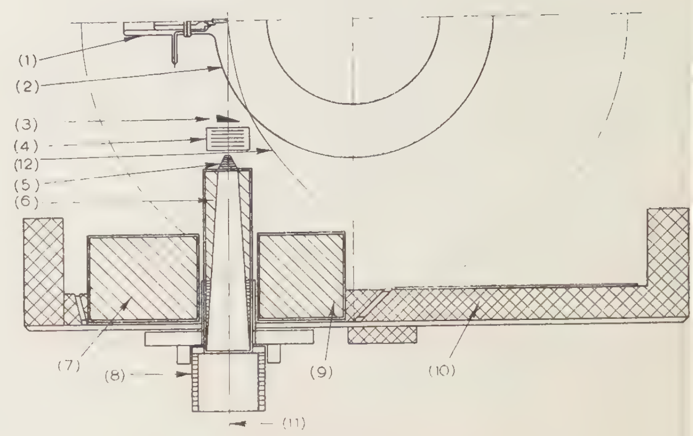

**Fig. 18.**—Collimator cross-section.

(1) Electron gun.
(2) Doughnut.
(3) Wedge filter.
(4) Ionization chamber.
(5) Beam flattener.
(6) Litharge collimator.
(7) Litharge.
(8) Applicator holder.
(9) Litharge.
(10) Cast lead shield.
(11) Axis of X-ray beam.
(12) Trajectories of high energy electrons bent by stray magnetic guide field.

adjustments on setting up give exact alignment of the collimator on to the X-ray target, and this is a finalized procedure for a given doughnut; electron-gun replacements alter the target position by less than 1 mm.

There are eight different treatment cones, with applicators, to give a variety of field shapes and sizes. The maximum size of field which can be irradiated is 14 cm diameter at 1 m from the target. Each treatment cone can be rotated relative to the collimator housing, so that rectangular treatment areas can be set at the required orientation for the patient.

The high-energy X-radiation (or bremsstrahlung) is produced by allowing the accelerated electrons to strike a target. The electrons are slowed down and deflected when they approach the individual nuclei of the atoms in the target. The theoretical spectral intensity of 18·5 MeV electrons is shown in Fig. 19,

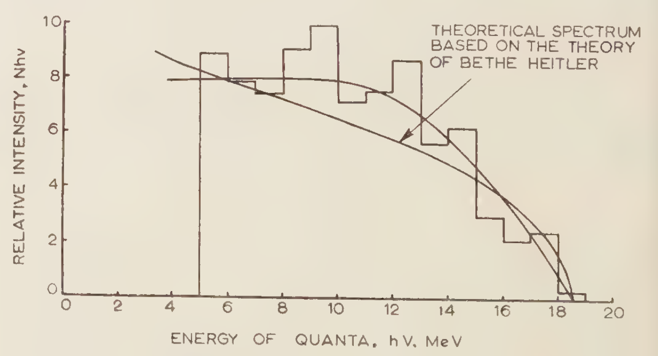


**Fig. 19.**—Theoretical and experimental intensity spectra.
The histogram is deduced from the energy distribution of the $H_2(\gamma n)\,H_1$ process.

together with the experimentally determined curve.[14] From these two curves it can be seen that the intensity is zero at the higher-energy tip, and increases gradually to the lower-energy end. The electrons normally strike the target at grazing incidence owing to the small spiral pitch of the expanding electron orbit, and produce a thin target spectrum. Some of the electrons pass through the target only to be scattered out of the doughnut. If the spiral pitch of the expanding orbit is increased, a thicker target may be used. Even though this will absorb more of the

electrons, the resultant spectral intensity will show an increase only in the number of low-energy photons.

The X-ray beam from the betatron, as with all high-energy accelerators, is in the form of a narrow cone in the forward direction, i.e. the direction in which the electrons are moving when they strike the target. The width of the cone varies inversely as the energy of the electrons and is proportional to the square root of the target thickness. For an energy of 20 MeV the half angle of the cone to half intensity is 4° 30′. There is a slight asymmetry of the X-ray beam owing to the circular motion of the electrons and their grazing incidence on to the target; the effective thickness of the target is greater on the side of the beam away from the centre of the doughnut.

To give uniform intensity across the treatment area, filters constructed of laminated copper are introduced. To overcome the asymmetry a wedge filter is permanently fitted adjacent to the doughnut. In addition, each treatment cone contains its own compensating filter. The smaller attenuation occurring with the smaller fields allows these to give higher intensities than if a single filter common to all treatment cones were used. In the case of the largest field the intensity after filtering is exactly half the unfiltered intensity. These filters have been designed and made by the Physics Section of the Christie Cancer Hospital. It is desirable to keep electrons which are scattered out of the doughnut, or those which originate in the filter out of the X-ray beam. The collimator is so designed that the curvature of the electron tracks, owing to the fringing field of the betatron magnet, causes nearly all the electrons to be stopped in the lead or Perspex of the collimator insert.

Fitted to each treatment cone is one of two Perspex applicators which delineates the treatment area and gives a target-to-skin distance of either 80 cm or 1 m to vary the treatment area. For lining up the patient, provision is also made for mounting an arm and arc or back pointer on the collimator housing.

The X-ray output of the machine is monitored by an ionization chamber mounted next to the wedge filter. The output measured here has to be corrected by a varying factor which depends on the particular treatment cone and applicator length to give the intensity at the patient. The ionization-chamber current is fed into a d.c. amplifier, of standard Medical Research Council type and designed to give dose rate and integrated dose readings on two meters, accurately to within 2%. The X-ray output can be made to cut off at a preset total dose or after a given time interval, and can be controlled from either the radiographer's control desk or the engineer's panel.

The depth-dose curves given in Fig. 20 compare the effects of X-rays of energies of 200 kV, 2 MeV and 20 MeV for the same field size. In clinical use, whilst a high dose is required to be delivered at a deep-seated tumour, the dose given to the skin at both the entry and exit of the beam has to be limited to avoid radiation burns, and the total dose received by the whole body must be kept as small as possible to avoid radiation sickness. The use of cross-fire techniques complicates the analysis, but for a tumour located well inside the body the use of 20 MeV X-rays gives reduced skin dose and total body dose compared with lower-energy radiation.

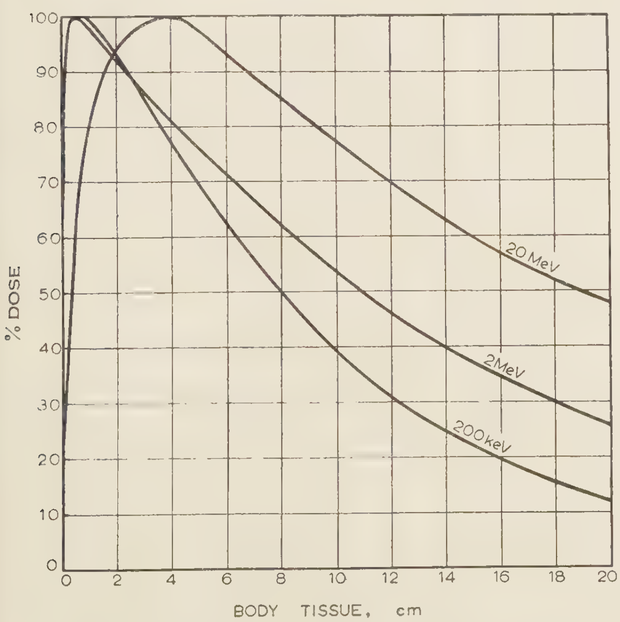


**Fig. 20.**—Depth dose curves for various voltages.

(10 × 10 cm fields 100 cm full-scale deflection.)

The depth dose rises more slowly with depth for 20 MeV radiation than for 2 MeV and 200 kV radiation, and reaches a maximum 4 cm below the skin.

## (6) CONCLUSIONS

By virtue of the development work on an earlier machine, a 20 MeV betatron has been installed for X-ray therapy which has a large X-ray yield. The machine is stable in operation and there is no reason why a similar machine could not be made completely controllable from the radiographer's desk. The electronic control equipment is comparatively simple, and consists essentially of two straightforward pulse circuits. Further developments to increase the X-ray yield would be to raise the betatron energy and to increase the injection voltage. Work on increasing the effective thickness of the betatron target and a more detailed study of the problem of injection could lead to further improvement.

A betatron has the advantage of easy variation of peak energy, and if it is found that electron therapy is useful it would be possible to extract the electron beam from the machine, and in this application, by varying the electron energy, the depth of penetration of the fast electrons could be controlled to suit the depth of the tumour.

## (7) ACKNOWLEDGMENTS

The authors wish to acknowledge the help given to them by all their colleagues in the betatron team, in particular Messrs. K. R. Allen and E. A. Finlay. Thanks are due to the members of the engineering drawing office for their help and advice; Mr. W. E. Edgar for his work on the structural design and erection of the machine; Mr. G. Croft for his invaluable assistance with the electronic equipment and Mr. G. Lovell for his patient endurance with vacuum plant. They are also indebted to the many engineers and fitters of Research and Erection Departments for their help and excellent workmanship which helped to make the project possible; also to Dr. Willis Jackson, F.R.S., Director of Research and Education, and Mr. B. G. Churcher, M.Sc., Manager of the Research Department, Metropolitan-Vickers Electrical Co. Ltd., for permission to publish the paper.

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# DISCUSSION ON "SHORT-CIRCUIT FORCES ON TURBO-ALTERNATOR END-WINDINGS"*

## BEFORE THE SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 7TH MARCH, 1955

**Mr. A. R. Blandford:** The films shown by the authors emphasize the necessity for better methods than visual inspection, combined with voltage tests for assessing the effect on the insulation on alternator windings when subject to short-circuit tests. To employ visual inspection successfully demands the characteristic—as yet unobtainable—of an elastic limit for the insulation equal to that of copper. To overcome these difficulties the authors have elected to construct a replica of an actual machine, with the object of measuring the movement of the windings while the short-circuit is in progress. This also permits over-voltage tests to be made and, in addition, the coils can afterwards be withdrawn and the insulation examined in detail.

Construction of a replica is a costly procedure, and it is unnecessary to produce one for every case. However, some such means seems to be the only satisfactory way of obtaining the necessary information on which to base new designs and so ensure that the bracing has a reasonable margin of safety without actually applying a full value short-circuit test to prove production machines.

**Mr. V. Easton:** In view of the widespread interest shown in the paper, sometimes by engineers who are not completely familiar with the subject, it is unfortunate that the very low sub-transient reactance of the 60 MW alternator—about 6%—is not specifically mentioned. This is approximately one-half of that normally expected for a machine of this rating, and the resultant high short-circuit currents will accentuate any difficulty which may occur. At the same time, experience with switchgear-testing alternators shows that the individual winding strips can be braced either to prevent any movement or to reduce it to such a value that it can be accommodated by the flexibility of the insulation without deterioration under conditions much more onerous than on commercial machines. The same principles of construction can be adapted to the latter.

One essential is to arch-bind the straight "stand out" of the conductors from the slots by using 3-piece wedges, supported radially and embracing both layers of conductor, which exert high and uniform circumferential pressure on the copper. Another essential is the consolidation of the insulation, not only where it is wedged, but also on the conical portions where the careful fitting of packing blocks at frequent intervals between strips again arch-binds the windings. A third essential is the provision of sufficient supports between the core end-plates and the back of the winding cone. A typical view of the end windings of an alternator embodying this construction is shown in Fig. C, the packing in effect providing support equal to that from the core but at some axial distance from it, so protecting the vulnerable point where most of the failures described in the paper occurred.

In the past, power-station operators have benefited greatly from short-circuit testing, which has ensured the development of robust windings capable of withstanding full-voltage tests at the machine terminals. The suggestion that this policy should be changed because, at present, the increase in alternator output is particularly rapid, has little justification. The greater output is being obtained by an improved ventilation technique rather than an actual increase in physical size; this will automatically result in higher inherent reactance, and conditions will not be so severe as suggested in Section 2.1, which uses as a basis machines 30 years old. It has been the policy of the organization with which I am associated to subject alternators of new design to a 3-phase 100% voltage test, and we see no necessity to make any modifications for machines up to at least 200 MW.

The data on the calculation of forces are open to criticism; in particular, it is difficult to account for the large difference in force on adjacent conductors shown in Fig. 4. Since the same fault current flows in the conductors of any phase, say conductors 51–60, at any instant the relative forces on individual conductors must be proportional to the radial flux density at their various positions. Oscillographic records taken on an actual alternator on open-circuit and on sustained short-circuit show radial-flux distribution substantially sinusoidal which, it is reasonable to expect, will not change markedly under transient conditions. Hence, when the force on conductor 51 is a maximum, the forces on conductors 52–60 should be only a little lower, owing to the sinusoidally distributed flux-densities. Have the authors measured the radial flux density at the knuckles of an actual alternator, as distinct from a model, under short-circuit conditions, to confirm the peaky distribution of flux density deduced from Fig. 4?

**Dr. W. G. Thompson:** While the testing of a full-scale replica of the end windings of a turbo-alternator may be useful in checking principles of design, there are fundamental objections to its use as a basis for acceptance tests. First, it is a test on only part of the design, and secondly, it does not take into account the possibility of slight differences in workmanship or quality of materials used.

* YOUNG, J. B., and TOMPSETT, D. H.: Paper No. 1683 S, July, 1954 (102 A, p. 101).

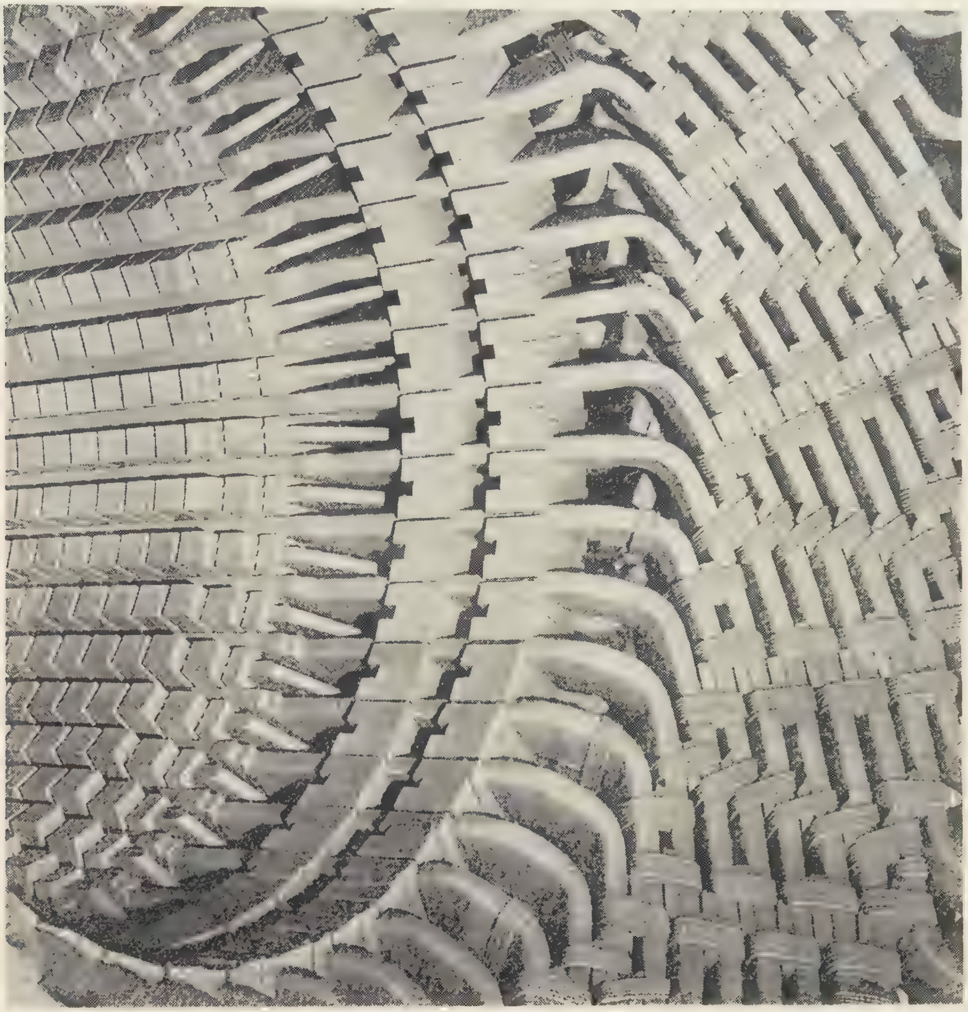

Fig. C

The tests described in the paper were presumably carried out with the normal arrangement for short-circuit testing in which the duration of the fault current is limited by a master circuit-breaker, whereas in the event of a short-circuit near the alternator terminals the duration of the fault current would depend upon how rapidly the excitation could be removed from the machine. Was this point taken into account in arranging the tripping time of the master circuit-breaker in the model test?

The behaviour of the windings during short-circuit (as revealed by the authors' film) suggests that, contrary to the views expressed in the paper, there might be some merit in trying to assess the local forces on the insulation in the machine. It would be interesting to know, for example, the degree of initial compression on the insulation produced by the binding and the extra pressure produced by the conductors rubbing together under short-circuit forces. The factors contributing to a tearing action could be elucidated by determining the coefficient of friction and the indentation pressure of the insulation. The possibility of permanent deformation might also be considered.

From a general engineering standpoint a conical shape is regarded as providing considerable strength, but it would appear that the repulsive forces between the two parts of the winding are so directed as to produce a straightening action of the curved bars, and hence a toggle effect at the knuckle, the remedy for which appears to be adequate supporting bracing and proper packing. Machines so constructed have properly withstood full short-circuit and subsequent insulation tests, and it seems that the case for abrogation of testing standards and substitute methods of testing as advocated by the authors remains unconvincing when considered in the light of alternative successful designs.

**Mr. F. D. Preston:** In the Introduction it is stated that short-circuit tests from full voltage represent progressively more severe and less realistic conditions as the sizes of individual machines increase. This statement requires examination.

Short-circuit forces depend upon short-circuit current, which, in turn, depends upon the sub-transient reactance. The reactances of a synchronous machine can be expressed per unit referred to constant maximum rated output by an equation of the form: Constant $\times A/B \times G$, where

$A$ is the linear useful load in ampere-conductors per centimetre (or per inch) of stator bore periphery.

$B$ is the fundamental induction in the air-gap, i.e. a mean flux loading.

$G$ is a function which includes the ratios of the geometric dimensions which vary with the reactance under consideration.

The induction, $B$, is nearly always chosen to be as high as possible, and can be taken as reasonably constant over the whole range of turbo-alternators. In other words, for a given physical or $D^2L$ size of machine, the working flux will not vary very much whatever the rating.

The function $G$, in relation to sub-transient reactances, includes

stator-slot and overhang leakages, which will vary with the physical layout of the machines concerned. Usually very little can be done to vary this quantity on a particular machine, although it is often possible to incorporate a so-called "reactance portion" above the stator-slot wedge, which increases the sub-transient reactance.

The function $A$ is one which increases considerably when advantage is taken of the more efficient forms of cooling which are the basis of present-day developments.

The present-day striking increases in output are not being obtained by building larger machines, but by utilizing more efficient forms of cooling, i.e. by increasing the ampere-conductors per inch of stator periphery. Hence, per-unit sub-transient reactances are larger, with the consequent decrease in per-unit short-circuit currents. This trend of obtaining greater outputs from the same size of machine, or the same output from smaller sizes, is likely to continue for some years.

It follows that the magnitude of the short-circuit forces depends more upon the physical size of the machine than on its output. Furthermore, physical sizes are not likely to increase much from the present-day maximum unless there are great improvements in materials available for rotor construction and facilities for transporting heavier loads than at present. Hence, maximum short-circuit forces on end windings are not likely to increase greatly in the future from those experienced at present.

**Mr. J. P. Harbord:** The authors suggest that it is unnecessarily severe to apply short-circuit tests from 100% terminal voltage on open-circuit. In service a more onerous condition may arise if a fault occurs close to the terminals when an alternator is on load. The fault current then depends upon the true internal voltage of the alternator and not upon the terminal voltage. This internal voltage, however, is less than the conventional generated voltage, which allows for the total stator leakage reactance $X_l$.

The internal voltage of an alternator is proportional to the total flux in the core. The overhang leakage flux has a true physical existence separate from the main flux and gives rise to a true reactive voltage drop, $IX_{l0}$, requiring an increase in the core flux to maintain the same terminal voltage $V_t$. The slot-leakage flux merely distorts and increases the tooth flux without affecting that of the core; it may be considered only as a fictitious reactive voltage drop, $IX_{ls}$. In calculating the flux in the core, therefore, and hence the true internal voltage $V_g$, one should make allowance for the overhang-leakage flux only and not the total stator leakage. Fig. D shows the full-load condition in a 60 MW 0·8-power-factor hydrogen-cooled

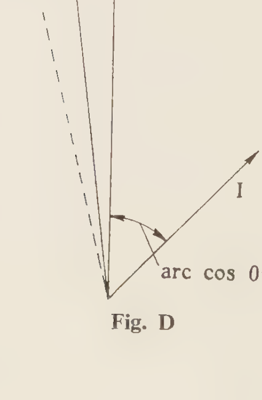


Fig. D

alternator having a total leakage reactance of 15%, of which $7\frac{1}{2}$% is due to overhang leakage. The internal voltage on full load is 104·8% of the terminal voltage (compared with a conventional generated voltage of 109·6%), and the short-circuit forces resulting from a fault on load may be 10%, but not 20%, higher than those from the same terminal voltage on open-circuit.

**Messrs. J. B. Young** and **D. H. Tompsett** (*in reply*): Progress in the design of robust bracing for alternator end windings has inevitably come at least partly from experience gained in short-circuit testing of production machines, but in principle it seems undesirable that this should be so. In our opinion there can be no justification for regarding the continuance of such tests as necessary when the stator winding forces are of the same order as those for which the adequacy of the end-winding bracing has already been proved by past experience or by some means such as a replica test. In this connection we agree with those speakers who suggest that, for the largest machines at present being constructed, the increased rating will not be accompanied by a proportionate increase in physical size, and the short-circuit forces will be of the same order as those arising in machines which have successfully withstood full-voltage short-circuit tests. Reference to forces on the windings of the first 200 MW alternator to be constructed in this country has been made in reply to earlier discussions. For still larger ratings some further increase in dimensions would undoubtedly be required, so that the range covered by the above arguments cannot be indefinitely extended. In our opinion the principles employed in designing switchgear-testing alternators cannot be at all readily adapted for conventional machines.

Two points must be recalled in connection with Mr. Easton's question on the conductor forces shown in Fig. 4. The first is that under sudden short-circuit conditions a stationary flux pattern is associated with the unidirectional components in the stator currents and a synchronously rotating distribution is associated with the alternating currents. Neglecting decrement, only the latter component is measured by a device such as a search coil, but it is the resultant of both components which must be considered when determining the local force on a conductor. The second point is that, owing to the configuration of the end-winding coils, the local flux distribution in the vicinity of the coil knuckles is only approximately sinusoidal. Even if it were sinusoidal, the time phase of the peak of radial components would be a function of the coil pitch, but would clearly not occur over the centre of the phase instantaneously carrying peak current, as Mr. Easton appears to be suggesting. A number of tests carried out on running alternators established the validity of the replica, and some of the results are referred to in the paper.

With respect to Dr. Thompson's remarks on fault-current duration, it would perhaps be correct in general to refer to the dissipation of the stored magnetic energy in the field as well as to the removal of excitation from the machine. Because of the rapid decrease in the short-circuit current, the first few cycles are the only significant ones so far as the forces are concerned: in fact, the master circuit-breaker was timed to operate after about ten cycles.

We have no knowledge of any trouble on stator end-windings arising from the compression of insulation due to tightness of binding, and in our opinion the tighter it is the better. It would be interesting to see a high-speed film of any end windings which Dr. Thompson would describe as having "adequate supporting bracing and proper packing to prevent movement."

Mr. Preston's analysis shows how it is that, as stated in Section 2, the short-circuit forces on the stator windings of recent large alternators are greater than those on earlier machines, because of the increased physical dimensions and higher current ratings. We do not consider that, in the event of a relaxation

of the test requirements, any manufacturer would risk his reputation by reducing the quality of stator-overhang bracing.

The discussion on the "true internal voltage" of a loaded alternator put forward by Mr. Harbord is at variance with the conventional treatment which regards the "voltage behind the sub-transient reactance" as the correct quantity to employ in the calculation of the initial short-circuit current. Mr. Harbord's arguments appear to be equivalent to an assumption that only the flux linkages associated with the overhang can change proportionally with current in the first few moments following a disturbance. In contrast, the usual assumptions made in estimating $x_d''$ lead to a result which is greater than the total stator leakage inductance, $x_l$, by an amount which is a function of the field-winding and damper-path leakage inductances and the magnetizing (or armature reaction) inductance.

In conclusion, we would say that our conviction remains that the larger and more expensive individual units become, the less desirable is it that they should be subjected to a succession of sledge-hammer blows before they are ever set to perform the duty for which they are designed, namely power generation.

# DIGEST OF AN INSTITUTION MONOGRAPH

## THE ELECTRIC STRENGTH OF TRANSFORMER OIL

621.315.615.2 : 621.3.015.5 Monograph No. 135 S

M. E. ZEIN EL-DINE, Ph.D., and H. TROPPER, Ph.D., Associate Member.

(DIGEST *of a paper published in June*, 1955, *as an* INSTITUTION MONOGRAPH *and to be republished in Part C of the* PROCEEDINGS.)

The object of the investigation was to examine a number of factors which affect the electric strength of transformer oil. To obtain reliable results is not easy, since the oil always contains various amounts of impurities and readily absorbs moisture and gases. Although normally the impurity contents may be small, they nevertheless lower the electric strength and cause considerable scatter of the measurements, which makes a correlation of the experimental results difficult.

Such a correlation would be greatly facilitated if the impurity content of the oil were known, or could be easily determined. In the absence of any practicable method, a test procedure was adopted which consisted in subjecting the oil to a number of cleaning operations in order to obtain as high an electric strength as possible. The electric strength of this treated oil was then used as a criterion for the state of its purity, and in this way the effect of adding impurities could be conveniently studied. It is believed that only by such a procedure is it possible to ascertain the extent to which various factors affect the breakdown mechanism of a complex dielectric liquid such as transformer oil.

The standard cleaning technique used throughout the experimental work consisted in drying the oil for several weeks in the presence of metallic sodium wire and silica gel. The oil was then degassed and filtered in a closed all-glass system of which the test cell formed an integral part. Preliminary tests, varying the number of degassing cycles, showed that the increase in the electric strength was most marked during the first five to ten cycles. Additional cycles did not produce any appreciable increase, and a point was soon reached when the change in electric strength was comparable to the variation of the individual measurements. These tests also revealed an interesting relationship between the gas content of the oil and the conditioning effect, namely the tendency of the electric strength to increase with increasing number of breakdowns. Whereas after only a few degassing cycles the electric strength of the oil increased continually with subsequent breakdowns, such an increase was found only during a small number of initial breakdowns when the oil was well degassed.

Accordingly, in all the experiments the normal treatment of the oil before the breakdown tests consisted of ten degassing cycles at a pressure of approximately 0·5 mm Hg with the oil at a temperature of 85–90°C. These values of temperature and pressure were also used for the subsequent filtration process, for which a sintered glass filter of porosity number 4 was used.

The electric strength of the oil treated in this way was very high. For uniform fields and using chromium-plated electrodes the strength was approximately 750 kV/cm for both direct and alternating voltages. This value was found to be independent of the gap setting for gaps varying from 0·1 to 0·5 mm, but for smaller gaps there was a tendency for the electric strength to increase with decreasing spacing. The corresponding value for impulse voltages was 1 500 kV and no change could be detected for the range of spacings from 0·5 to 0·1 mm. With this type of voltage there was again a marked increase in the electric strength when the gap setting was further reduced, and very high values could be obtained for very small gaps. For example, for a gap of $15 \times 10^{-3}$ mm an electric strength of about 6000 kV/cm was measured when a 1/3 microsec impulse was used. Since breakdown was observed to occur approximately 1 microsec after the crest value of the impulse, it is to be expected that even higher values would result with impulses of shorter durations.

For treated oil no change of the electric strength was found when the tail of the impulse voltage was varied from 100 to 15 microsec. For shorter tail length the electric strength increased and a value of 1 900 kV/cm was obtained for a tail of 3 microsec, which was the shortest used in the experiments. However, when the oil was not specially treated but only filtered at room temperature and atmospheric pressure with a filter of porosity number 2, not only were the electric strengths found to be smaller, but they decreased when the duration of the impulse was increased from 1 000 kV corresponding to 20 microsec tail to 950 kV when the tail was 100 microsec.

The effect of the electrode metal on the breakdown strength of treated oil was examined for the metals chromium, silver, aluminium, stainless steel, steel, copper and brass. These tests showed that there was a marked effect when direct voltages were used. Copper, for example, gave electric strengths which were 40% higher than those obtained with brass electrodes. It was found that the metal of the electrode and the treatment of the electrode surface affected not only the measured electric strength but also the conditioning effect. For example, for chromium electrodes about 13 preliminary discharges were needed, whilst for silver electrodes 30 discharges were necessary to obtain breakdown values which showed no tendency to increase further. The effect on the electric strength of treating the electrode surface can be seen from the results obtained with

Dr. Zein El-Dine is in the Faculty of Engineering, University of Alexandria. Dr. Tropper is in the Electrical Engineering Department, Queen Mary College, University of London.

steel electrodes after they were degassed by heating them for three hours under a vacuum of $10^{-3}$ mm Hg. This treatment resulted in an increase in the electric strength from 900 to 1 300 kV/cm.

For impulse voltages no dependence of the breakdown values on the electrode metal could be detected. With this type of voltage there was also no effect on the breakdown when the gap was irradiated with $\gamma$-rays from a cobalt source, which, in the case of direct voltages, resulted in a slight lowering of the breakdown voltages.

For the tests with non-uniform field configurations a point-plane gap was used. Tests on treated oil using direct voltages showed a polarity effect, the negative breakdown being higher than the positive. The breakdown values for alternating voltages were identical with those for direct voltages of positive polarity, and in both cases the breakdown occurred in the form of intermittent discharges which quickly quenched themselves and were accompanied by sharp clicking noises.

With impulse voltages the polarity effect was found to be reversed, and slightly higher voltages were required for the breakdown when the polarity of the point was positive. Hence for this type of voltage and for treated oil the polarity effect is similar to that observed for pure organic liquids of simple molecular structures.

The polarity effect for direct voltages is very sensitive to the impurity content of the oil. The addition to the treated oil of a small quantity of spherical polystrene particles of 10 microns diameter brings about a lowering of the breakdown voltage which is practically the same for the two polarities. On the other hand, the polarity effect is enhanced when gas is added to the treated oil. The presence of the gas in the oil can be appreciable, and tests on oil saturated with gas gave lower breakdown values than treated oil when the polarity was positive, but the breakdown values were higher than for treated oil when the polarity was negative.

Interesting in this connection are the results which were obtained when the treated oil was tested under different external pressures. For uniform field configurations and direct voltages practically no change in the breakdown voltage could be observed when the external pressure was increased from atmospheric pressure up to 200 lb/in$^2$. For the same pressure range and non-uniform fields an increase of the breakdown voltage with increase of external pressure was found only for the negative breakdown. A short exposure of the test sample to air resulted in a somewhat greater pressure dependence of the breakdown voltage, and moreover, this dependence now occurred for both polarities.

Throughout the experimental work a striking difference could be observed in the experimental results according to the type of test voltage used. With impulse voltages and treated oil the results were, without exception, of the kind which one would obtain under similar conditions for very pure simple organic liquids. This suggests strongly that electric breakdown in both cases is due to a similar mechanism.

For direct voltages, on the other hand, the tests have shown the important part played by the gas contained in the oil. In this case a bubble mechanism is suggested for the explanation of the breakdown. It is assumed that two processes are involved. The first consists in the formation of gas bubbles in the liquid at (or near) the cathode by the strong breakdown fields and the introduction of electrons into the liquid by the ionization of these bubbles. The second process consists of an adequate electron multiplication by gaseous ionization in the bulk of the liquid. As shown in the paper, this mechanism, although over-simplified and incomplete in several important details, is capable of explaining qualitatively fairly well the main features of the experimental results.

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# INDEX TO VOLUME 102, PART A

**1955**

ABBREVIATIONS

(P)—Address, lecture or paper.
(p)—Subject dealt with in a paper or address.
(D)—Discussion on a paper.
(A)—Abstract or digest of an address or a paper.

## D

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PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, DECEMBER 1955

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*Example.*—Smith, J.: "Overhead Transmission Systems," *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 (102 A, p. 1234).



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